

NASA Contractor Report 156866

# Design Definition of a Microwave Power Reception and Conversion System for Use on a High Altitude Powered Platform

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MICROWAVE POWER RECEPTION AND CONVERSION  
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**NASA**

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**Wallops Flight Center**  
Wallops Island, Virginia 23337  
AC 804 824 3411



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## SUMMARY

This study was concerned with the design definition of a microwave power reception and conversion system for use on high altitude powered platform. The scope of the study was enlarged to include an initial design, construction and test effort on the thin-film, printed-circuit rectenna which the early part of the study concluded was the direction in which to proceed.

The first-phase of the development of a thin-film, printed-circuit rectenna was satisfactorily completed. This is defined as the fabrication and testing of a single element of the foreplane structure which contains all elements of the rectenna with the exception of the reflecting plane. The starting material was laminate of one mil Mylar and two 0.8 mil copper cladding material. Using standard photoetching techniques the copper on both faces was etched away to leave the microwave circuitry. The diode rectifier was then added. Initial testing of one of the rectenna elements in the standard rectenna test element indicated that the approach was basically satisfactory. The projected DC power output from such a rectenna is 130 watts/meter<sup>2</sup> and the measured mass is 77 grams, giving a figure of 1.69 kW/kg for the power to mass ratio. It is estimated that after allowances are made for the mass of reflecting plane and foreplane separators that a power to mass ratio of 1 kW/kg can be obtained.

Diode material that had previously been expressly made for rectenna use was packaged for the first time in a miniature low-cost glass package and incorporated into the thin-film printed-circuit rectenna.

The heat dissipation capability of the rectenna element in a purely radiative environment was investigated. Guidelines for the series-paralleling of elements to produce the desired current and voltage output, and for computing buss bar losses were developed. Several approaches to attaching the reflecting plane were suggested but an actual selection and development of an approach was not undertaken.

A special effort was made to evaluate the impact that the design and size of the rectenna has upon the overall cost of the microwave power transmission system. The findings were that the rectenna should be quite large in diameter to minimize cost as well as improve efficiency.

It was concluded that there was a conflict between the optimization of the microwave power transmission system and the conventional dirigible-shaped vehicle because of the limitation that such a vehicle makes on the diameter of the rectenna as well as upon its rotational alignment with the ground transmitter. An investigation of other possible aerostat configurations was initiated and reported upon.

A study of a low-altitude demonstration of an airborne rectenna was made starting with the assumption that a fifty-foot mechanically steerable parabolic reflector at the Wallops Flight Center would be retrofitted with a low microwave power source consisting of a five-kilowatt commercially-available magnetron and that a small blimp would be used to support the rectenna.

## 1.0 INTRODUCTION

In recent years a number of studies have been made of the application of microwave-powered platforms that could fly continuously at high altitudes in the earth's atmosphere. An altitude of 21.33 kilometers (70,000 feet) has often been specified. These studies have indicated that there are a substantial number of potential applications for such platforms but that both technical and economic feasibility need further study. (1.5)

In examining the technical and economic feasibility of the system, three things must be considered. These are the microwave power transmission system, the platform vehicle, and the compatibility of the microwave power transmission system and the platform vehicle. Microwave power transmission technology has reached the point in its development where there should be no serious question about the ability to transmit the required amount of power to the vehicle, but there have been many questions about the interface of the receiving system with the vehicle. The cost of the microwave power system transmission system has also been well defined.

As to the platform itself, the possibilities are the aeroplane, the helicopter, and the aerostat. The latter is defined broadly as a balloon or dirigible which can maintain station rather than drift with the wind. All of these platform vehicles, when considered in combination with the microwave power system, have their advantages and disadvantages. The aerostat has the advantage in that it presents a relatively large receiving aperture area which can substantially reduce the cost of the microwave power transmission system.

The major purpose of the study was to produce a reference design from which interface areas could be defined. In order to define this reference design, a set of assumptions which were compatible with the state of the art of microwave power transmission and the air vehicle was given in the work statement.

These assumptions included a dirigible-shaped vehicle of about 500,000 cubic feet capacity with a fineness ratio of 4. There was a DC power output requirement of 43 kilowatts at 230 volts to operate the motors needed for propulsion to keep the aerostat on station during periods of high winds. The payload requirement was to be limited to one kilowatt at 28 volts.

The set of microwave power system assumptions included a frequency of 2.45 GHz which is compatible with the transmission requirements through heavy precipitation and which is the frequency where all of the development of microwave power transmission, including substantial system testing and component development, has been carried out. It also included linear polarization which again reflected the direction in which the technology had developed as well as the recognition of the difficulty of rectenna construction of polarization other than linear. Finally, an initial assumption of an incident power density of 175 watts per square meter upon the receiving antenna was made.

It was recognized that this set of initial assumptions would lead to a rather specific rectenna design which could be regarded as a reference design. It was also desired that the study should be general enough to express as many of the interrelationships as possible in a parametric form to allow the systems designer a broader selection of rectenna size.

Another initial condition for the study was to use as much available rectenna technology as possible in order to minimize the cost and development time that would be needed for new approaches. This aspect combined with the set of initial assumptions as to power requirements and aerostat shape led to the concept of an inflatable parabolic reflector within the aerostat envelope that would collect the energy and concentrate it upon a rectenna that would be constructed from rectenna elements already well established by extensive test and system demonstration. The rectenna could rotate with respect to the parabolic reflector to always be aligned with the transmitter on the ground.

After an initial examination and comparison with other approaches, this approach seemed to be inferior in principle to an approach that would make use of etched or "printed" microwave circuits that would duplicate the electrical properties of existing designs but which would be supported on thin Mylar film. However, there had never been any technology development devoted to such an approach so that it was not wise to consider a design based upon it. But, an initial investigation indicated that a modest investment of effort would probably make it possible to obtain enough experimental data to develop the confidence necessary to proceed with a design based upon this approach.

A decision was therefore made to follow up the thin-film printed-circuit approach and the contract was modified to include this as a task. At the same time it was agreed to deemphasize some of the other parts of the study, particularly that having to do with back-up electrical power systems.

As a result of the decision, this study has contributed significantly to the technology of microwave power transmission, particularly for the aerostat application, by undertaking the first-stage development of a thin-film, printed circuit, and following it through the analysis, design, fabrication, and testing stages to the point where it can be used as the basis for confident statements with respect to efficiency, DC power output density, and mass per unit of power output.

It was also recognized that one of the major outputs needed from the study would be an estimate of the cost of the rectenna, both in terms of eventual production costs for such rectennas as well as an estimate of the costs for developing and constructing the first full-scale rectenna for the high-altitude vehicle. Provisional estimates of the production cost were developed dependent upon the production costs of diodes which are a principal element of cost in the rectenna. Even in this area, the study took the first steps to reduce the cost of the special GaAs Schottky-barrier diode that is needed for this application by repackaging in the small glass package which is the universal approach to achieving lowest possible cost in diodes.

With respect to the cost aspect, it has been recognized that one of the important elements necessary for making a decision on whether to proceed with the development of high-altitude microwave-powered platforms is a more accurate estimate of the cost of the microwave power transmission system as a whole. So it has also been an objective of this study to obtain a better understanding of the interrelationship of the rectenna design to the cost of the overall microwave power transmission system. The cost analysis that was made utilizes an excellent mathematical relationship between the costs of the various parts of the system, and a much better base of component cost than has hitherto been available.

The cost and technical data developed under this study constitute a basic input for the vehicle and systems designer. In particular, the vehicle designer has at his disposal a source of continuous electrical power of almost any desired amount with the mass penalty of less than one kilogram per kilowatt at a projected cost penalty that includes the ground transmitter ranging from \$14,000/kw for the system as defined in the statement of work to less than \$5,000/kw for a more optimum system. This represents a new factor that could profoundly impact the design and mission of the high-altitude atmospheric platform. Various sections of the text of the report provide some insight into this potential impact upon design. An important technical input that may be basic to new aerostat configurations is the special study that was done by Professor Ham of Massachusetts Institute of Technology.

The balance of the introduction is devoted to the organization of the report. The first subject covered in Section 2.0 is the relationship of the rectenna to the overall system in terms of cost. It is found here that the size of the rectenna is a variable of great importance in minimizing cost.

The second investigation in Section 3.0 covers the first-phase design, construction and testing of the thin-film, printed-circuit rectenna. It also contains a derivation and assessment of many of its pertinent characteristics such as mass, efficiency, thermal dissipation, etc. It contains an estimate of the cost to finish the rectenna development and construct the first rectenna to meet the reference design requirements.

Section 4.0 deals with the physical incorporation of the rectenna into the aerospace vehicle, and the various conflicts that arise. There is a discussion of other approaches to vehicle design.

Section 5.0 deals briefly with how an auxiliary microwave beam reference can fulfill the needs of the aerostat vehicle for attitude and position references. It also discusses the basics of the retrodirective array system and the approximate power requirements in the aerostat.

Section 6.0 contains a discussion of the changes that have taken place in the approach to a scaled-down demonstration of microwave power transmission to an aerospace vehicle that would demonstrate flight-weight rectenna hardware.

Section 7.0 is a summary of rectenna characteristics that would be of value to the vehicle or system engineer.

Section 8.0 is devoted to a concise summary statement of the results of the study.

Section 9.0 is a brief statement of concluding remarks and recommendations.

Several reference articles are listed in the bibliography, to which the reader may wish to refer to obtain a broader perspective or obtain general information on the technology of microwave power transmission which was not included in the general text. References on special topics are called out in the text when they become relevant to the discussion.

Finally, the help and advice of Sheldahl Inc. of Northfield, Minnesota, in reviewing the thin-film printed-circuit design and in furnishing the laminate material, is acknowledged. They also participated in the planning of a scaled-down demonstration.

## 2.0 OVERALL MICROWAVE POWER TRANSMISSION SYSTEM COSTS

### 2.1 Introduction

An adequate understanding of the cost of the system is of key importance to making decisions relative to further development of the concept. Because of its importance, it will be treated in considerable detail in this section.

The initial cost of a microwave power transmission system consists basically of the cost of the ground transmitting installation and the cost of the rectenna at the receiving site. The cost of the beam-steering feature which is referred to as the retrodirective array principle is included in the cost of the ground-transmitting installation. An auxiliary system may be needed to position the aerostat and keep it in proper attitude, but this is not included in the system cost. (6,7)

The costs of the ground portion and the vehicle portion of the microwave power transmission system are closely related and an analysis of this is the principal subject of Section 2.0.

The projected cost of the ground transmitter, which consists of the two cost components of radiating antenna and microwave power generation, has historically varied over a range of ten to one depending upon the underlying assumptions and who was doing the estimating. However, the recent information that has been obtained on the successful use of the microwave oven magnetron in the transmitter permits an accurate estimate of the cost of the microwave power. (8) And, even more recently, a low cost method for forming thin-walled slotted waveguide array modules has been introduced and successfully evaluated through construction of engineering samples. (9) The method has established the cost of material for the ground array and has provided the basis for a labor input analysis to provide a good estimate of cost. Also, recently, the phase and amplitude tracking that is necessary for the retrodirective array principle has been experimentally evaluated to make it possible to also project these costs which are considered to be part of the antenna-array costs.

The projected cost of the rectenna can also be accurately estimated if it is assumed that the diode cost will follow the historically well-documented costs on other diodes as they are produced in even larger quantities. A principle reason for being able to accurately estimate the cost of the rectenna (without the diode cost included) is the work that has been carried out under this study on the thin-film printed circuit rectenna.

A serious restraint upon the options available to both the cost analyst and systems designer is that the system has maximum efficiency only when the transmitter and rectenna are rotationally aligned with respect to each other. If they should be out of rotational alignment by  $90^\circ$  the efficiency of the system would go to zero. Since the aerostat, if it is assumed to have a conventionally streamlined cigar-shape, is expected to have to change heading with a change in wind direction, the restraint places a serious limitation on how the rectenna is

deployed in the aerostat. However, the removal of this restraint by attempting to design a circularly polarized system does not appear to be a tractable approach. The present approach to a low cost, low-mass thin-film printed-circuit where the DC buss bars are on the same plane as the half-wave dipoles is compatible with a linearly polarized system but not with a circularly polarized system. The rectenna design for a circularly polarized system would be forced into a three-plane system with the bussing carried behind the ground plane with a great increase in cost and mass of the rectenna.

In any event, there would be a serious time delay and increased cost involved in attempting to utilize such a system, since none of the components have been designed and experimentally evaluated as has been the case for the linearly polarized system.

## 2.2 Cost Analysis

### 2.2.1 Results

At the onset of the study it was recognized that an advantage of the aerostat vehicle was that it could support a relatively large receiving antenna, but just how this was related to the cost of the microwave power transmission system was not known. The present study has worked out the relationship of size of the rectenna to cost of the system and shown it to be of critical importance.

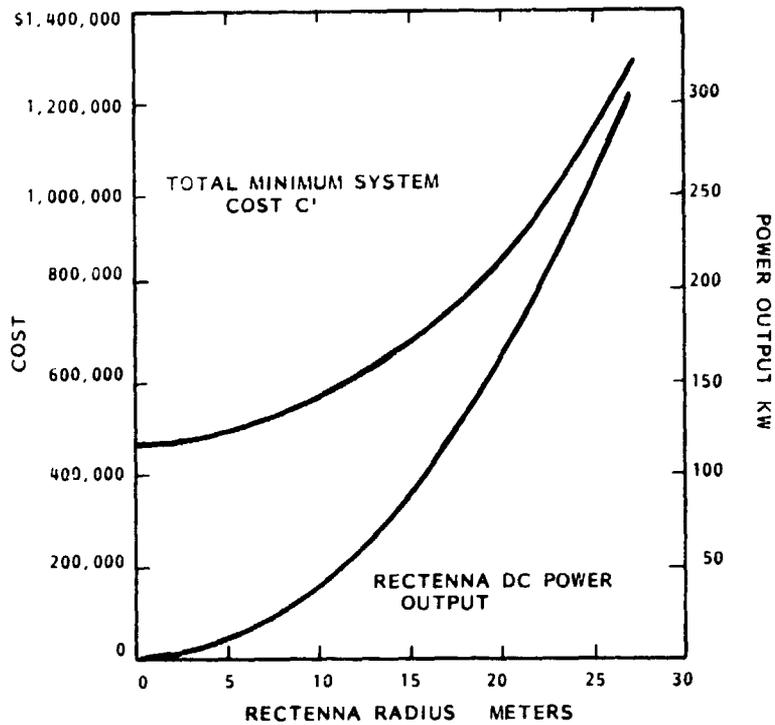
The results of the cost analysis in terms of the rectenna radius is shown in Figure 2-1. Plotted on this figure are (1) the minimum total system cost as a function of the size (radius) of the rectenna, and (2) the DC power obtained from the rectenna operating at the value of 185 watts/square meter<sup>1</sup> of incident microwave power and an assumed conversion efficiency of 70 percent. (These values are consistent with the experimentally observed power handling and efficiency performance of the thin-film, printed-circuit rectenna described in Section 3.0). The total cost is seen to vary by a factor of only 2.5 to 1 while the DC power output varies from 0 to 300 kilowatts.

Figure 2-2 breaks down the minimum total system cost  $C'$  into its principal components: (1) the rectenna cost  $C_r$ , (2) the transmitting antenna cost,  $C_t$ , and (3) the cost of the facility to generate the microwave power,  $C_p$ . It is of interest that for minimum total system cost, the cost of the facility to generate the microwave power is actually less for the largest rectenna radius and largest DC power output than it is for zero radius and zero rectenna power output. One would not anticipate this intuitively and the finding illustrates the need for treating the cost problem in an analytical way to arrive at the minimum cost.<sup>2</sup>

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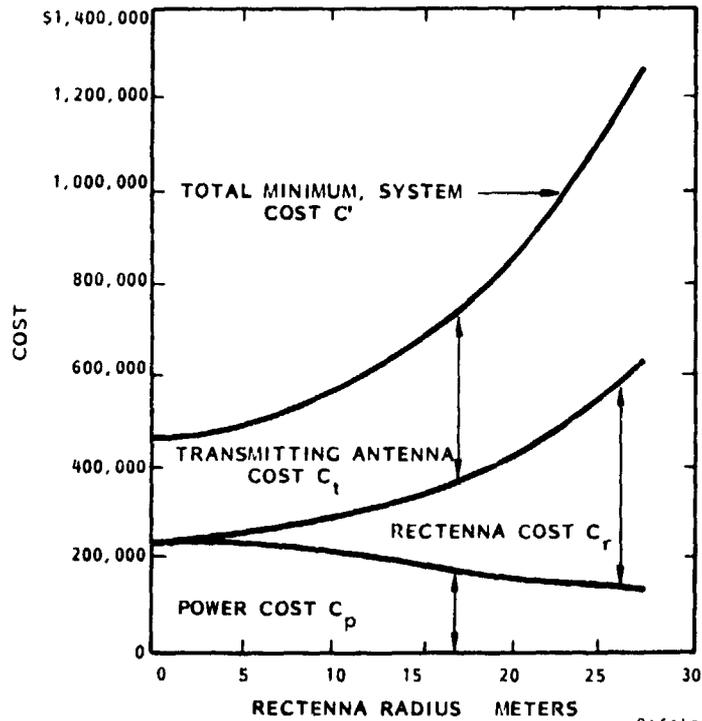
<sup>1</sup>See item 12 in Section 2.2.2.

<sup>2</sup>This analysis does not include the vehicle costs.



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Figure 2-1. System Cost and System DC Power Output as Function of the Rectenna Dimensions (Radius).



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Figure 2-2. System Cost Broken Down into (1) Power Cost, (2) Transmitting Antenna Cost, and (3) Rectenna Cost as Function of the Rectenna Size (Radius).

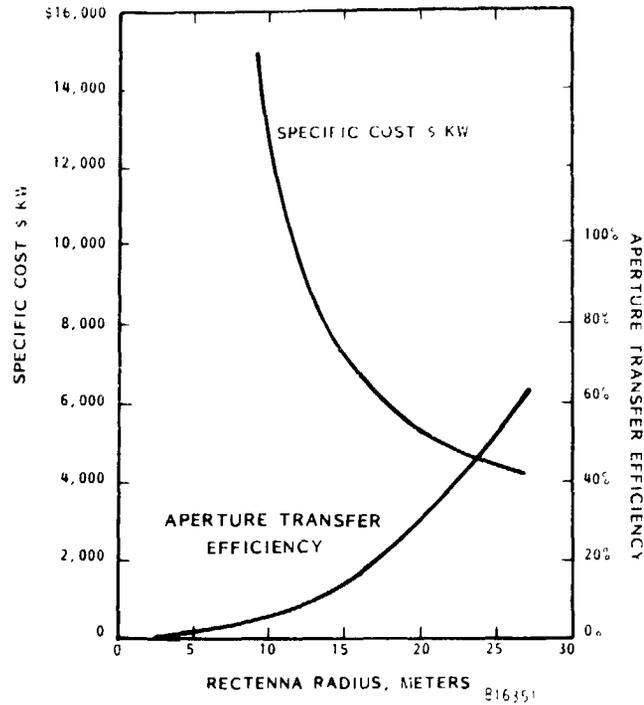


Figure 2-3. Specific Cost of Microwave Power Transmission System and Aperture Transfer Efficiency as Function of Rectenna Size (Radius).

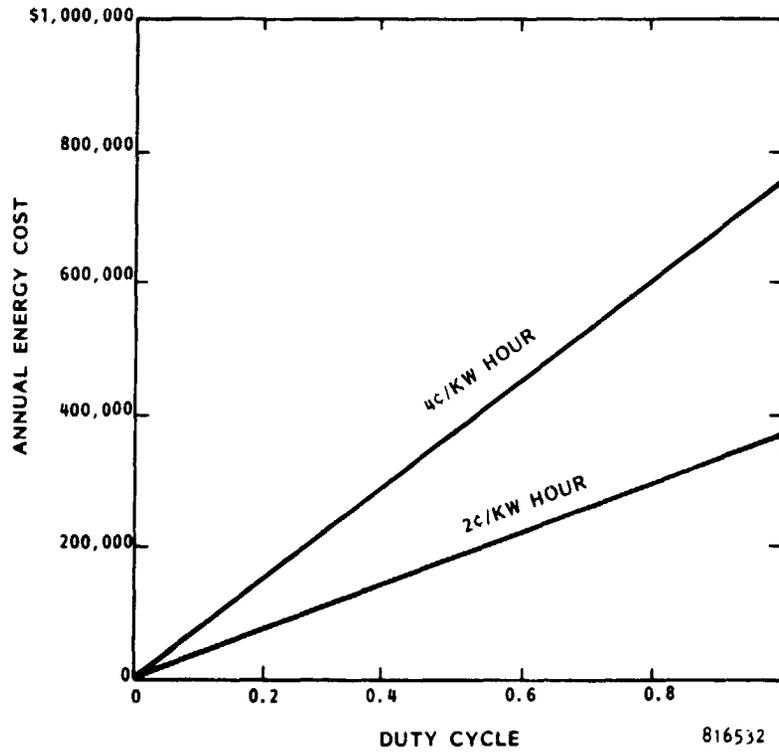


Figure 2-4. Annual Electrical Energy Costs as a Function of Duty Cycle and Cost of Energy. System is assumed to be operating with the rectenna output of 44 Kw, an aperture transfer efficiency of 4.6%, a rectenna efficiency of 70% and a DC to RF conversion of 65%.

Figure 2-3 presents additional relationships and data that are of interest. It shows specific system cost, defined as the ratio of total system cost to total kilowatts of DC power output. This is seen to vary from an extremely high figure to a value of \$4,210 per kilowatt at the largest rectenna radius of 27.2 meters. It is of interest that the referenced rectenna size (19.82 meters in diameter or 9.91 meters radius)<sup>3</sup> supplies 39.9 kilowatts of power at a system cost of \$449,000 or \$14,000 per kilowatt. Plotted also on Figure 2-3 is the aperture transfer efficiency and it is seen that an increase in efficiency improves the specific cost, as would be anticipated.

The operation of the system will consume electrical energy. However, in the high altitude aerostat application the system will be used at its maximum power level for only those infrequent periods when the winds are very high. The payload fraction is assumed to be very low. Figure 2-4 shows the yearly cost of the energy consumed as a function of the duty cycle and the cost of electrical energy for the reference system derived from the statement of work. A radiated power level of 1366 kilowatts was derived from a rectenna DC power output of 44 kilowatts, a rectenna efficiency of 70 percent, and an aperture-to-aperture transfer efficiency of 4.6 percent. The 60 cycle power requirement would then be 2102 kilowatts based upon a 60-cycle-to-microwave conversion efficiency of 65 percent.

It is of interest that the energy cost is 1.98 times that of an optimum system which supplies 300 kilowatts from the rectenna as compared with 44 for the reference design.

#### 2.2.2 Discussion of Assumptions

In the cost analysis the following assumptions were made:

1. Engineering charges for development have been written off and the systems have reached the routine production phase.
2. Cost is defined to include material, labor, overhead, and reasonable general and administrative expenses, but not profit.
3. Cost of energy consumed was not considered.
4. Cost of land preparation, footings, and installation for transmitting antenna not included.
5. Any protective requirements (such as a radome) for adverse weather conditions not included, as this is a function of the location of the installation.

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<sup>3</sup>See item 12 in Section 2.2.2.

6. Cost of prime power (diesel engine, electric utility, etc.) not included.
7. Rectenna will be used at its maximum rated power density on some occasion, regardless of the physical size of the rectenna.
8. Cost of installed microwave power source is \$200/kilowatt including any AC to DC power conversion.
9. Cost of rectenna is \$215/meter<sup>2</sup>. Includes self protection but not power conditioning for load, if the latter should be necessary.
10. Cost of transmitting antenna is \$215/meter<sup>2</sup>.
11. Aperture transfer efficiency given by Goubau relationship (see Section 2.4).
12. An incident power density of 185 watts/m<sup>2</sup> was inadvertently used in place of the reference value of 175 watts/m<sup>2</sup> in the statement of work. However, the impact on cost is well within the uncertainty of other cost elements.
13. Transmitting and receiving apertures are circular.
14. Retrodirective array cost included in \$215/meter<sup>2</sup> for transmitting antenna and \$200/kilowatt for microwave power source.

### 2.3 Cost of Microwave Power, Transmitting Antenna, and Rectenna

Of these assumptions, those dealing with the cost of the microwave power, the transmitting antenna cost, and the rectenna cost deserve special discussion because cost estimates assigned to them determine the overall minimum system cost.

#### 2.3.1 Cost of Microwave Power (Iter 8)

The use of the microwave oven magnetron in combination with ferrite circulator and phase and amplitude tracking servos is assumed. Cost of the power supply and tube in microwave ovens is \$60 for 700 watts of delivered microwave power, or \$86 per kilowatt. Hence, a production cost of \$200 per kilowatt is assumed reasonable for the aerostat application where three-phase power source and scale-of-power supply should reduce power-supply costs while control circuits and ferrite circulator will increase the cost. Current cost of tubes is \$25 each and they can be used in this application at the one-kilowatt level. Current cost of ferrite circulators in microwave oven applications is \$20.00. Control circuitry and external tube modifications may cost \$30.00 per kilowatt extra.

These costs will seem low to the designer of microwave equipment of the communications or radar type. But a microwave power transmission system does not fall under that classification. It is much closer in nature to a microwave power source designed for industrial microwave processing. In this commercially active area the cost of the microwave power is \$400 per kilowatt. A more conservative but not necessarily more accurate estimating approach would be to use this higher figure. However, the higher figure will not greatly impact the overall cost of the complete microwave power transmission system.

### 2.3.2 Cost of Transmitting Antenna (Item 9)

The assumed cost of the transmitting antenna is \$215/meter<sup>2</sup>. The transmitting antenna is largely identified with the slotted waveguide array. The new technique described in Reference 16 will result in very low material and fabrication costs when the tooling for production is completed. Made from 0.0508 centimeter thick aluminum, the weight of the antenna is only 4.53 kilograms per square meter and the corresponding material cost is less than \$15/meter<sup>2</sup>. The assembled array is adequately strong so that no increase in material thickness is needed. The labor cost should be low with production tooling and will largely be identified with assembly costs. The total cost (labor, overhead and G&A) associated with assembly should be no more than \$50/meter<sup>2</sup>. The balance of the \$215/meter<sup>2</sup> cost is associated with the retrodirective array principle.

### 2.3.3 Cost of Rectenna (Item 10)

The estimated rectenna cost of \$215/meter<sup>2</sup> is assumed to be equally divided between the diode cost and the balance of the rectenna. The balance of the rectenna includes the thin-film printed-circuit foreplane, the reflecting plane, and the arrangement for spacing the two from each other. An assumed diode cost of \$0.50 each in a glass package is predicated upon the experience with other diodes similarly packaged where prices (as distinguished from cost) are now as low as \$0.02 (2 cents each). Although the GaAs diode chip in the form it is made for the rectenna is more expensive to manufacture than many other diode chips, it is not that much more expensive.

The thin-film printed circuit itself should be very low in cost in production quantities -- about \$20/meter<sup>2</sup>. This would leave about \$90/meter<sup>2</sup> for adding the diodes and the reflecting plane.

## 2.4 Cost Analysis Procedure

This total system cost may be approached by breaking down the system into the following parts, each of which has a cost associated with it: (1) the cost of the transmitting antenna, (2) the cost of microwave power generating equipment, and (3) the rectenna in the aerostat vehicle. It is assumed that the costs of both the transmitting antenna and the rectenna are proportional to their area, since both are composed of modules or sections that are assumed to have been produced in such large quantities that costs per unit area are stabilized.

The total cost of the complete microwave power transmission system will therefore be:

$$C = C_t + C_r + C_p \quad (2-1)$$

where  $C_t$  is the cost of the transmitting array  
 $C_r$  is the cost of the rectenna  
 $C_p$  is the cost of the microwave power.

If we make the assumption that a unit area of the transmitting antenna costs "a" dollars, and that a unit area of the rectenna costs "b" dollars and that a unit of microwave power costs "m" dollars we may rewrite (2-1) to obtain:

$$C = a\pi r_t^2 + b\pi r_r^2 + \frac{m\pi r_r^2 P_d}{n} \quad (2-2)$$

where  $r_t$  is the radius of the transmitting antenna  
 $r_r$  is the radius of the receiving antenna  
 $P_d$  is the average microwave power density incident upon the receiving aperture  
 $n$  is the microwave power transfer efficiency between the transmitting and receiving antennas.

The first two terms in (2-2) are linked through an expression originally developed by Goubau (Reference 10 and Figure F-4 of Reference 15) which states that

$$\Gamma = \frac{\pi r_t r_r}{\lambda D}, \text{ where} \quad (2-3)$$

$\Gamma$  is a number related to the desired transmission efficiency  $n$ . For values of efficiency between 10 - 62 percent with which we will be concerned initially:

$$\Gamma = \frac{n + 0.18}{0.8} \quad (2-4)$$

Also in (2-3).

$\lambda$  = the wavelength of transmission

$D$  = separation between transmitting antenna and rectenna.

If the quantity for  $\Gamma$  from (2-4) is substituted into (2-3), the expression for  $r_t$  is:

$$r_t = \frac{(\lambda D)(n + 0.18)}{0.8 \pi r_r} = \frac{k_1}{r_r} \quad (2-5)$$

If we substitute this into (2-2), we obtain:

$$C = \frac{a \pi k_1^2}{r_r^2} + b \pi r_r^2 + \frac{m \pi r_r^2 P_d}{n} \quad (2-6)$$

But we are interested in finding the minimum cost. To find this we will find  $r_r$  for minimum cost,  $r_r'$ , and then substitute this in equation (2-6) to obtain the minimum cost.

$$\frac{dC}{dr_r} = \frac{-2a \pi k_1^2}{r_r^3} + 2b \pi r_r + \frac{2m \pi P_d}{n} r_r = 0 \quad (2-7)$$

from which

$$r_r' = \left( \frac{a k_1^2}{b + \frac{m P_d}{n}} \right)^{1/4} = \left[ \frac{\left( \frac{\lambda D (n + 0.18)}{0.8 \pi} \right)^2}{b + \frac{m P_d}{n}} \right]^{1/4} \quad (2-8)$$

$r_r'$  from (2-8) may then be substituted into (2-6) for  $r_r$  to obtain the minimum cost  $C'$ . The expression (2-8) is a general expression. To apply it, it is necessary to assign values to  $a$ ,  $b$ ,  $m$ ,  $P_d$ ,  $n$ ,  $\lambda$ , &  $D$ . The reference design assigns values of 21,336 meters to  $D$ , 0.1224 meters to  $\lambda$ , and 185 watts/m<sup>2</sup> to  $P_d$ .<sup>4</sup>

A cost of \$215/m<sup>2</sup> is a realistic production cost for  $a$  &  $b$ , and \$200/kilowatt a similar cost for  $m$ . (See Section 2.3 for further justification.)

If these values are substituted into (2-8), the expression for  $r_r'$  becomes:

$$r_r' = \frac{123.6 (n + 0.18)}{\left( 215 + \frac{37}{n} \right)^{1/4}}^{1/2} \quad (2-9)$$

In expression (2-9), the rectenna radius for minimum system cost is seen to be a function of the aperture transfer efficiency. The relationship holds for values of transfer efficiency ranging from 10 percent to 62 percent. A more general relationship holds for all values of efficiency ranging from 0 to 100 percent but it is necessary to go back to non-linear regions of the relationship between  $n$  and  $\Gamma$  as given in Figure 2 of Reference 10 to obtain this relationship.

<sup>4</sup>See item 12 in Section 2.2.2.

Using the relationship in (2-9) to find  $r_r$ , and substituting it into (2-6), a set of costs associated with  $C_t$ ,  $C_r$  and  $C_p$  and the minimum system cost,  $C'$ , have been generated and are shown in Table 2-1. Also shown on this table are the dimensions of the transmitting antenna, the DC power output from the rectenna, and the specific cost. Much of this data has been used in the preparation of Figures 2-1, 2-2 and 2-3.

In Table 2-1 calculations have also been made for the minimum cost of systems having a transfer efficiency of less than 10 percent. In the limit of the rectenna area going to near zero, there is no rectenna cost of importance, and the problem simplifies to finding the lowest cost system comprised only of transmitting antenna and power generation costs that will provide the power density needed at the rectenna receiving site. An expression for such minimum cost has been derived in reference 17 and is given below

$$C' = 2 \lambda D (amP_d)^{1/2} \quad (2-10)$$

where:  $\lambda$  is the wavelength of the microwave radiation  
 $D$  is the separation distance of transmitting and receiving apertures  
 $a$  is the cost per unit area of the transmitting antenna  
 $m$  is the cost per unit amount of microwave power  
 $P_d$  is the power density at the receiving site.

If the same values for the variables that have previously been used are inserted into (2-10), the transmitting antenna radius for minimum cost is 18.46 meters (121-foot diameter) and the minimum cost is \$460,000, equally divided between transmitting antenna and power costs.

Calculations that were made between 0 and 10 percent aperture transfer efficiency are subject to a small error because of the difficulty of reading the relationship between  $\Gamma$  and  $n$  from the Goubau curve (even in its original full page form in reference 10), or taking the other approach and adding the cost of the rectenna to the simple relationship from which (2-10) was derived. However, further refinement at this time does not appear merited.

Another aspect of the mathematical model is that the Goubau relationship assumes an optimum distribution of illumination over the transmitting antenna and the receiving antenna. For low efficiencies, this illumination pattern approaches uniform density. For the highest efficiencies considered in our analysis, the illumination is tapered but the ratios involved are still compatible with the ability of the rectenna to handle the increased power density at the center implied by the tapered illumination as well as to operate efficiently over the range of power density involved in the taper. Thus, the mathematical model that was used for cost is still reasonably accurate up to the highest aperture transfer efficiency that was considered, 62 percent.

TABLE 2-1

MINIMUM COST OF POWER TRANSMISSION SYSTEM AS  
FUNCTION OF APERTURE TRANSFER EFFICIENCY

n Percent	$r_T'$ (3) meters	$r_t$ meters	$C_t$ (4) \$ x 1000	$C_r$ (4) \$ x 1000	$C_p$ (4) \$ x 1000	$C'$ (4) \$ x 1000	Rectenna DC Power kW	Specific Cost \$/kW
62	27.2	30.6	630	499	138	1267	301	4210
50	24.7	28.6	552	412	142	1106	249	4440
40	22.5	26.8	484	341	147	972	206	4720
30	19.89	25.1	424	267	153	844	162	5200
20	17.1	23.2	378	196	168	742	118	6290
10	13.3	21.8	323	119	206	647	72	8960
(1) 5	9.32	19.6	260	59	202	521	35	14760
(2) 4.6	(5) 9.91	18.6	247	66	247	559	40	14100
(2) 0	0	18.5	230	0	230	460	0	

(1) Using Goubau  $n - \Gamma$  relationship

(2) Using Equation 2-10 + Rectenna Cost

(3) from equation 2-9

(4) from equation 2-6

(5) See item 12 in Section 2.2.2.

### 3.0 CONSTRUCTION AND TESTING OF THE FIRST-PHASE DESIGN OF A THIN-FILM, PRINTED-CIRCUIT RECTENNA; ASSESSMENT OF CHARACTERISTICS; ESTIMATE OF COST TO COMPLETE DEVELOPMENT AND FABRICATE REFERENCE DESIGN

#### 3.1 Introduction

An outstanding result of the study was the successful construction and testing of a single rectenna section made with precision pattern and etching techniques. This was considered to be the critical achievement since the individual element is repeated many times in the foreplane, and the foreplane represents most of the difficulty in rectenna design since it contains the microwave circuit, the filters, the rectifier, and the DC bussing.

The construction of the thin-film printed circuit is shown in Figures 3-1 and 3-2. Figure 3-1 is an artist's cutaway drawing of the structure while Figure 3-2 shows the completed structure of the first-phase design.

From a fabrication point of view, the structure is almost ideal. Parts of the microwave circuit appear as copper etchings on both sides of the film but there are no interconnects from one side to the other, and the registration of one side with the other is not highly critical.

The diode is the only element of the circuit that needs to be added to the thin-film printed circuit.

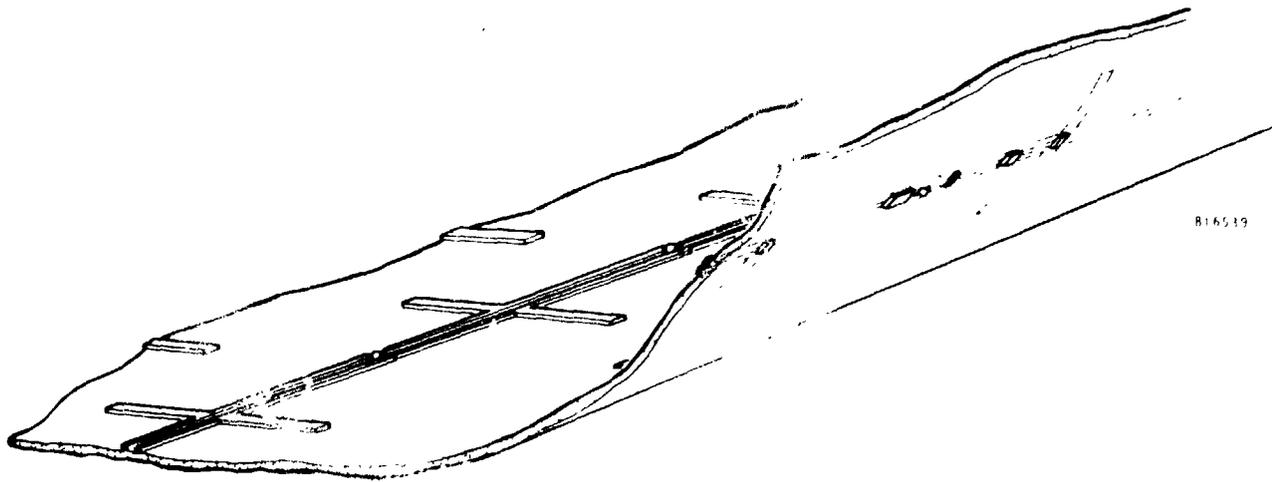
The diode has special requirements imposed upon it, and the diode especially developed for the thin-film, printed circuit meets those requirements. The diode must be in a small package that can be mounted to the printed circuit. The small glass package that was used for this purpose also makes the diode potentially very low in cost when it is made in large numbers. The diode needs a plated heat sink to keep the internal temperature gradient to a minimum. Finally, the etched circuit needs to reach a high temperature to radiate the waste heat and this can only be accomplished with a diode material that will operate at high temperature. GaAs is such a material.

To obtain the highest possible efficiency from the diode, the thickness of the epitaxial layer was carefully controlled to minimize the series resistance which is a major source of loss in the diode.

The printed circuit development effort and the use of the special diode has resulted in a design that approaches the projected efficiency and which exceeds the original projection of power-handling capability.

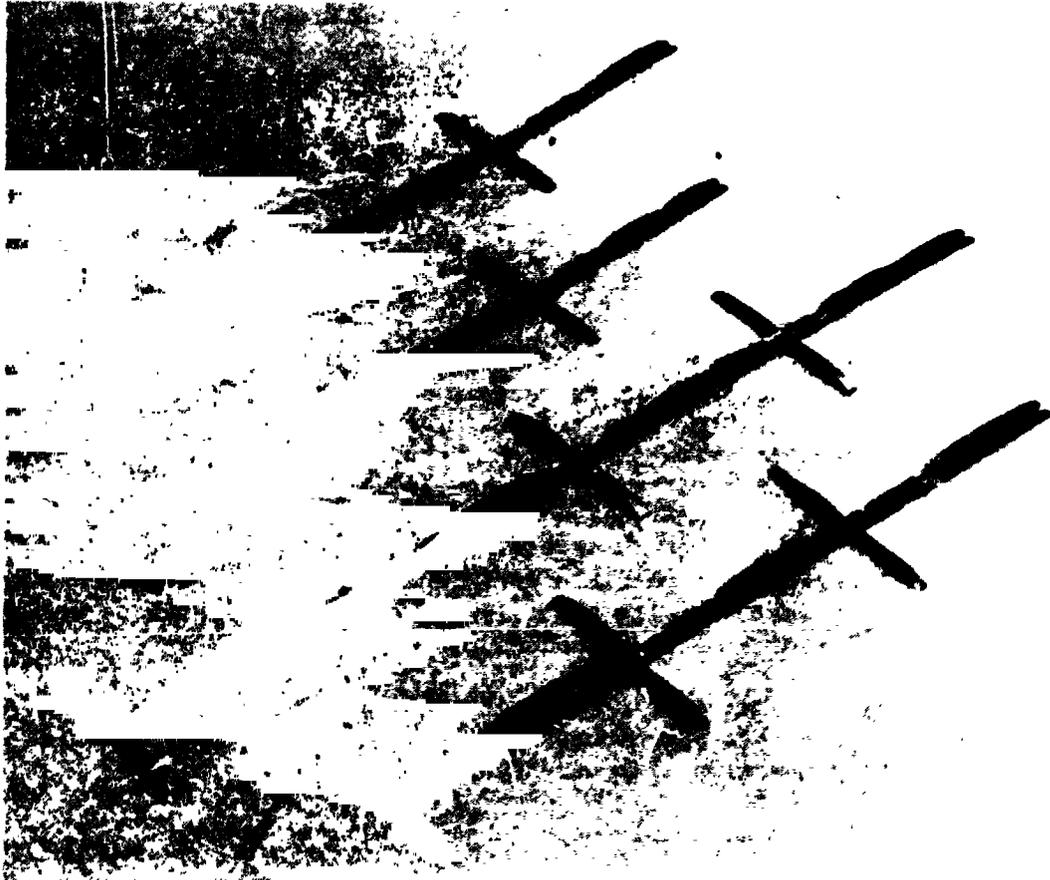
In the following material these subjects will be treated:

- (1) Initial test results.
- (2) Selection of the basic design approach.
- (3) Design of the electrical circuit and physical layout of the circuit.



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Figure 3-1. Flexible Rectenna.



80-1036C

Figure 3-2. Photograph of Thin-Film Rectenna.

- (4) Diode design and test.
- (5) Heat dissipation capability of the design.
- (6) Methods of mask preparation and fabrication of the thin-film, printed-circuit.
- (7) Design options for combining the foreplane and reflecting plane of the rectenna.
- (8) Load matching and bussing of the DC power;  $I^2R$  loss in bussing.

### 3.2 Initial Test Results

The initial test results are identified with those obtained from a single rectenna element. This is consistent with the general procedure in rectenna development in which the individual rectenna element is tested in a closed system so that its absorption efficiency and overall efficiency can be accurately measured.<sup>(11)</sup> The test fixture is shown in Figure 3-3. It consists of a section of 430 waveguide whose height is expanded to allow the insertion of the rectenna element to be tested. Figure 3-4 is a closeup of the rectenna element under test. The rectenna element is mounted on a flap door which is closed and clamped during the actual testing. The metal door seals in all microwave energy and acts as a reflecting plane for the rectenna element.

A schematic of the test arrangement is shown in Figure 3-5. Accurate measurements of incident and reflected microwave power are made on the input side while the DC power is measured on the output side. A precision resistance box is used as a load and the voltage across the load is measured with an accurate digital voltmeter to determine the output power.

Figure 3-6 shows the output efficiency of the rectenna element as a function of the value of the resistive load,  $R_L$ , and the power absorbed by the rectenna element. Figure 3-6 also indicates the amount of reflected power as a function of resistive load and the power absorbed by the element. The maximum efficiency obtained was 72 percent.

The area occupied by an element in the rectenna is approximately 50 square cm. At an incident microwave power density level of 175 watts per square meter, this would correspond to an incident power per element of 0.88 watts.

Figure 3-7 shows the output efficiency as a function of frequency at one value of resistive load and one value of microwave input power. A maximum efficiency of 74 percent was obtained at 2400 MHz.

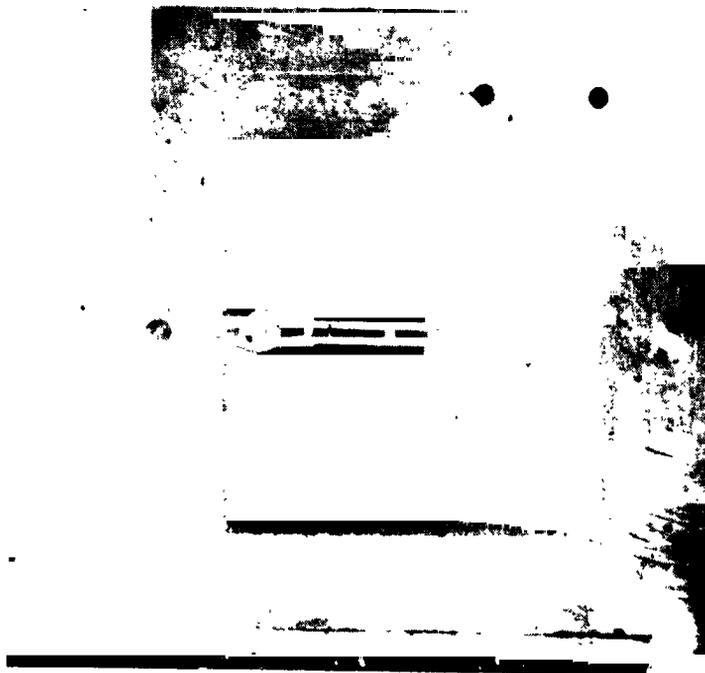
#### 3.2.1 Discussion of Test Results

In general, the efficiency figures are about 5 percent lower than expected. Higher circuit losses in the printed circuit format as compared to the heavier construction previously used are to be expected, but they appear to be larger than expected.



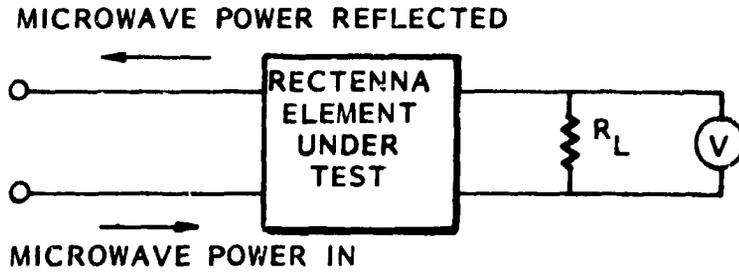
79-84458

Figure 3-3. Test Fixture for Testing an Individual Rectenna Element. Thin-film printed-circuit is shown on hinged door which is closed and clamped onto end of expanded waveguide during test.



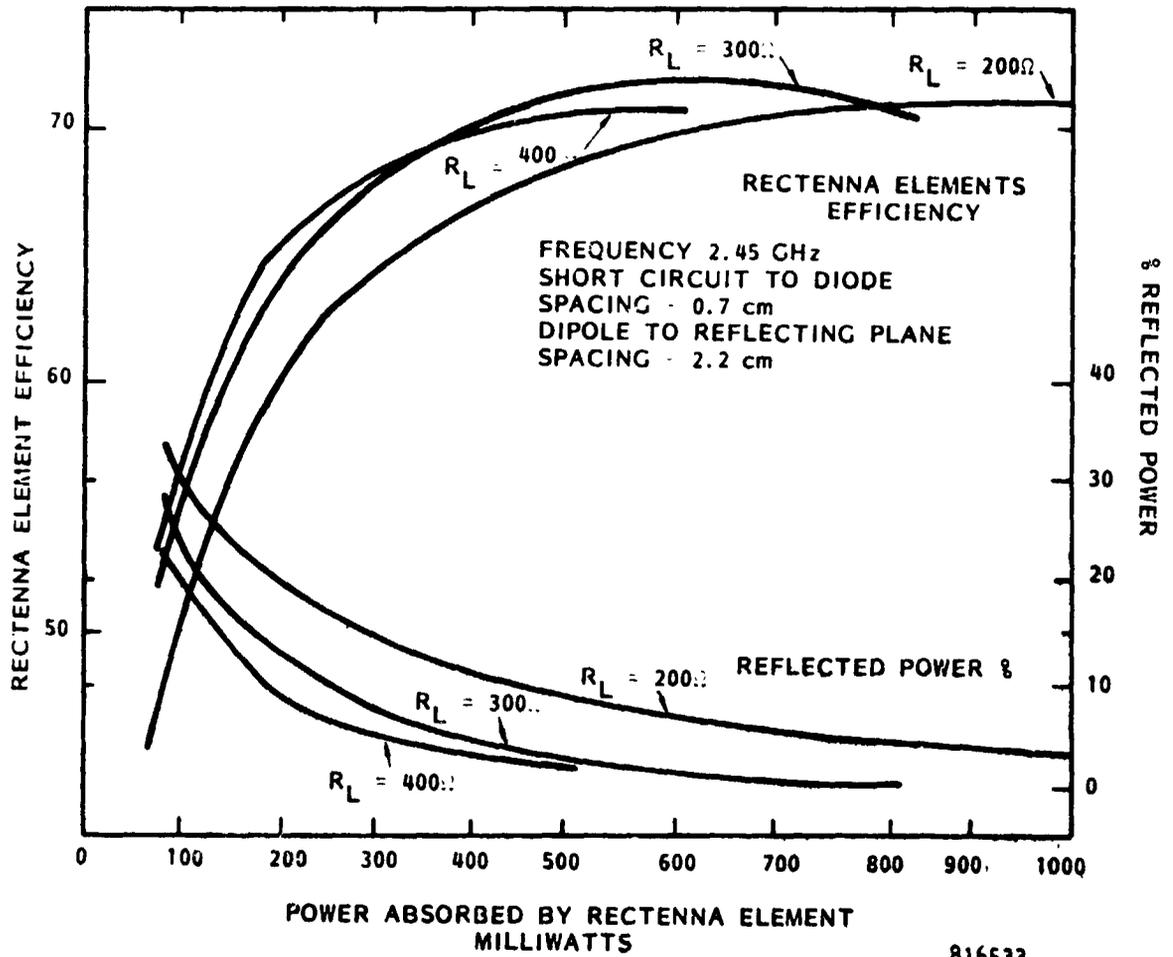
80-10356

Figure 3-4. Thin-Film Printed-Circuit Rectenna Element, Shown in Test Position in Fixture.



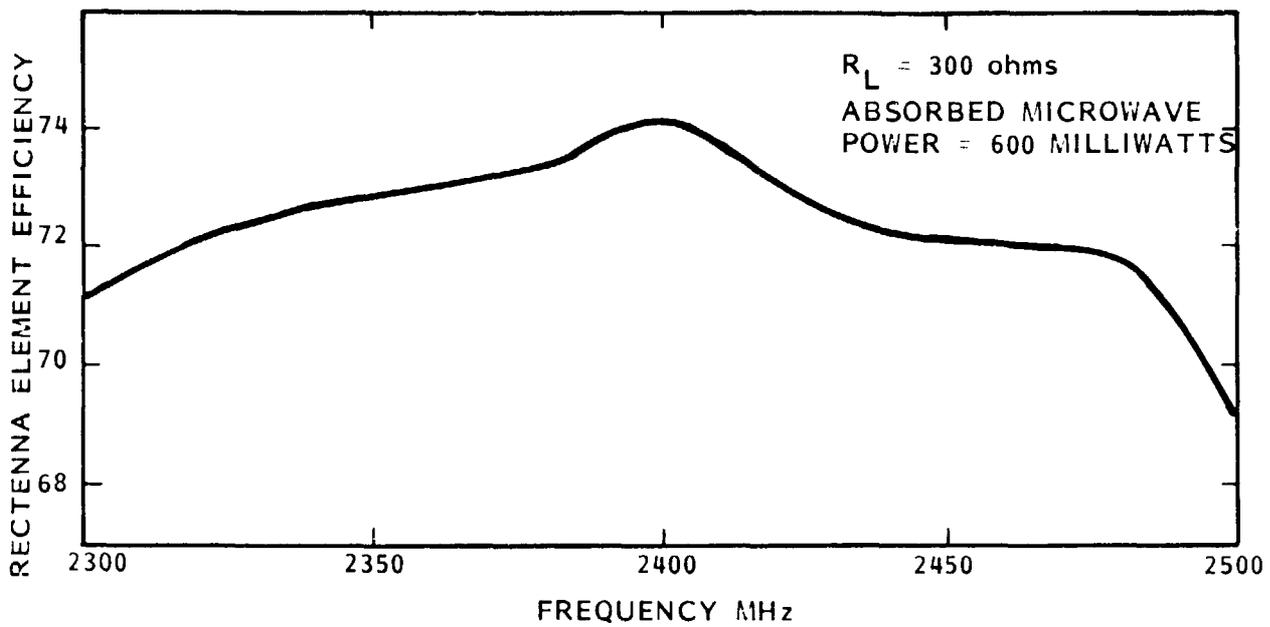
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Figure 3-5. Simplified Schematic of the Test Arrangements in the Rectenna Element.



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Figure 3-6. Test Results on Rectenna Element Shown in Figure 3-4.



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Figure 3-7. Efficiency Behavior of Printed-Circuit Element as a Function of Frequency.

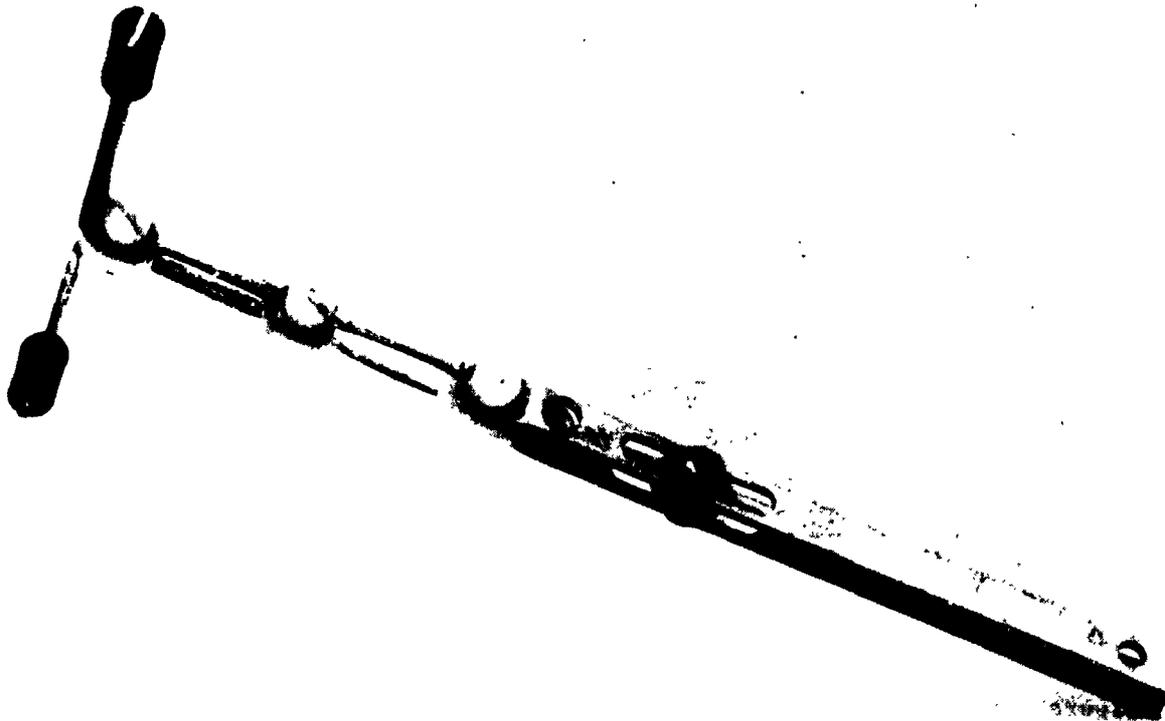


Figure 3-8. RXCV Rectenna Element that Served as a Model for the Design 77-78992 of the Thin-Film Printed-Circuit Element.

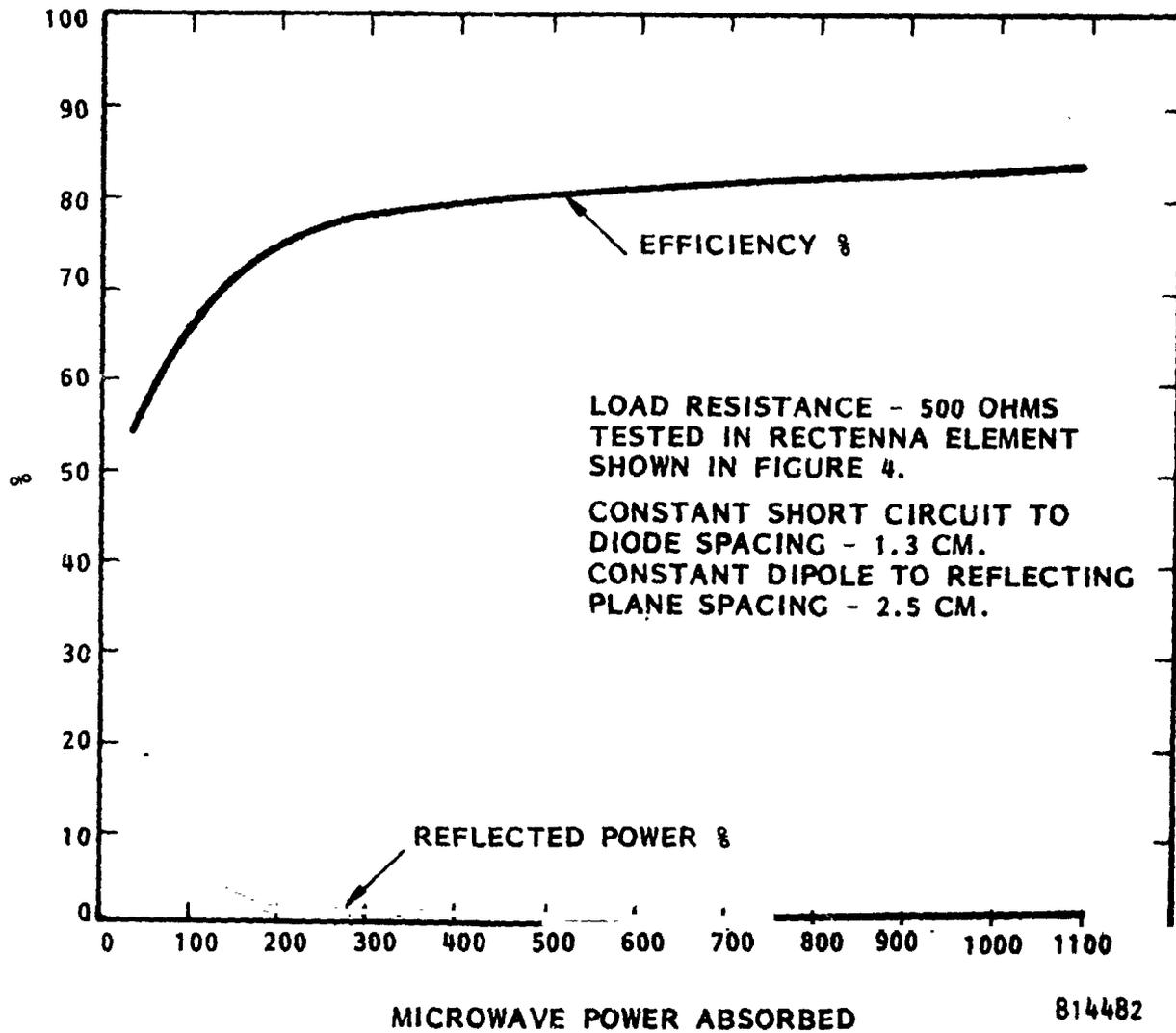


Figure 3-9. Efficiency and Reflected Power as Percent of Absorbed Microwave Power for the Combination of Specially Designed Microwave Diode and the Rectenna Circuit of Figure 2-8.

A good comparison reference is the performance of a rectenna element composed of another diode from the same sample lot but with the heavier construction of the circuit shown in Figure 3-8. Its performance is shown in Figure 3-9. The efficiency at 600 milliwatts input was 80 percent as compared with a maximum efficiency of 72 percent at 2450 MHz and 74 percent at 2400 MHz obtained from the printed circuit with the same microwave power input. However, the element was operating into 500 ohms in Figure 3-9 which would reduce the inefficiency caused by the Schottky barrier voltage drop. Unfortunately, the use of a high value of load resistance with the printed-circuit element caused the efficiency to become less as higher microwave power inputs were used. The explanation of this difference in performance is either in a difference in the value of reverse voltage breakdown for the two diodes or a difference in the duration of the conduction period, because these two factors determine the maximum value of the DC voltage output. Clearly, a determination should be made of which it is.

There was a limited amount of tailoring of the rectenna element to maximize performance. For example, the efficiency at 2450 MHz was increased from 65 percent to 72 percent by reducing the length of each leg of the dipole antenna by one millimeter. This simple adjustment resulted in improving the efficiency at the higher frequencies, but the data of Figure 3-7 indicates that a further shift is desirable. More tailoring of and more test data on the present design would be desirable.

At the present time it is not clear as to the reason for the reduced efficiency of the thin-film printed-circuit element from that expected. The reduced efficiency could be caused by losses in the adhesive used to bond the copper to the Mylar, for example, or it could have been caused by a poor performance of the particular diode that was used. Clearly, additional testing and tailoring of the rectenna element are desirable.

### 3.3 Selection of the Basic Design Approach to the Thin-Film Printed-Circuit Rectenna

A basic assumption in all the design effort is the use of 2.45 GHz as the frequency of power transmission. The basic philosophy in the selection of an approach was that the resultant product must be attractive in terms of a tradeoff between electrical performance, mass per unit of DC power output, and economy of construction, and that there be good confidence in the successful outcome of the development.

This latter aspect argued for basing the design as closely as possible upon past developments which have proven electrically sound but which are not of the thin-film printed-circuit format. Several results from these efforts are directly applicable to the thin-film printed-circuit approach. The first of these

is the development of the two-plane rectenna format in which all of the rectenna functions (including bussing of DC power), with the exception of the simple reflecting plane, are carried out in one plane called the foreplane.<sup>5</sup> A second is the application of high impedance circuitry and special diodes to improve the efficiency of operation at relatively low-incident microwave power densities which will be typical for the aerostat application.

The ratio of the mass or weight of the rectenna to the DC power output is a very important consideration in the design. Because much of the aerostat technology is already associated with thin plastics to minimize its weight, it is natural to think in terms of using similarly thin film in the construction of the rectenna.

The mass of the rectenna is comprised of the mass of the foreplane, the mass of the reflecting plane, and the mass of the means of spacing them from each other. The reflecting plane consists of a very thin film that is metallized to a depth of two skin thicknesses, or about  $2 \times 10^{-4}$  cm. Its mass can be kept very small.

In the foreplane there are several parameters associated with mass that must be considered. First there is a minimum cross section of the transmission-line conductors for efficient conduction of the DC power which must be transported over an appreciable distance. Secondly, there must be a cross section of the conductors near the point of diode attachment to carry away the diode dissipation. Since the conductors radiate the heat, it is desirable to have the conductors of considerable width. The microwave circuit requirements suggest that the conductors be large in area but that the thickness may be kept small. The Mylar film is another item that contributes to mass and should be kept as thin as possible. It is also desirable to keep it thin from an electrical point of view. But, if it gets too thin, maintaining a thickness tolerance on the fabrication of the Mylar becomes a problem.

An estimate of the mass of the foreplane per unit area can be made from the projected design discussed in Section 3.4, which seems to be adequate from the diode cooling, efficient DC bussing, and mechanical strength points of view. This design, which is made from a sandwich of  $2.54 \times 10^{-3}$  cm (1 mil) Mylar and two facings of 28.35 gm (1 oz.) copper<sup>6</sup>, gives a total mass of 77 grams per square meter. The total mass is broken down into 37 grams of Mylar, 30 grams of copper, and 10 grams of diodes. This translates into a ratio of mass per kilowatt of DC power of 0.628 kilograms per kilowatt if a DC power output density of 122.5 watts per square meter is assumed, a figure that is consistent with the reference density of 175.

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<sup>5</sup>NASA CR-135194 Electronic & Mechanical Improvement of the Receiving Terminal of a Free Space Microwave Power Transmission System. William C. Brown, Raytheon Company, Prepared for NASA Lewis Research Center. August 1, 1977, Pages 75 to 99 and 50 to 74.

<sup>6</sup>28.35 gm copper refers to 28.35 gm (1 oz.) of copper per .093 m<sup>2</sup> (1.0 ft.<sup>2</sup>). The corresponding thickness is  $3.556 \times 10^{-3}$  cm (1.4 mils). The material was provided by the Sheldahl Company.

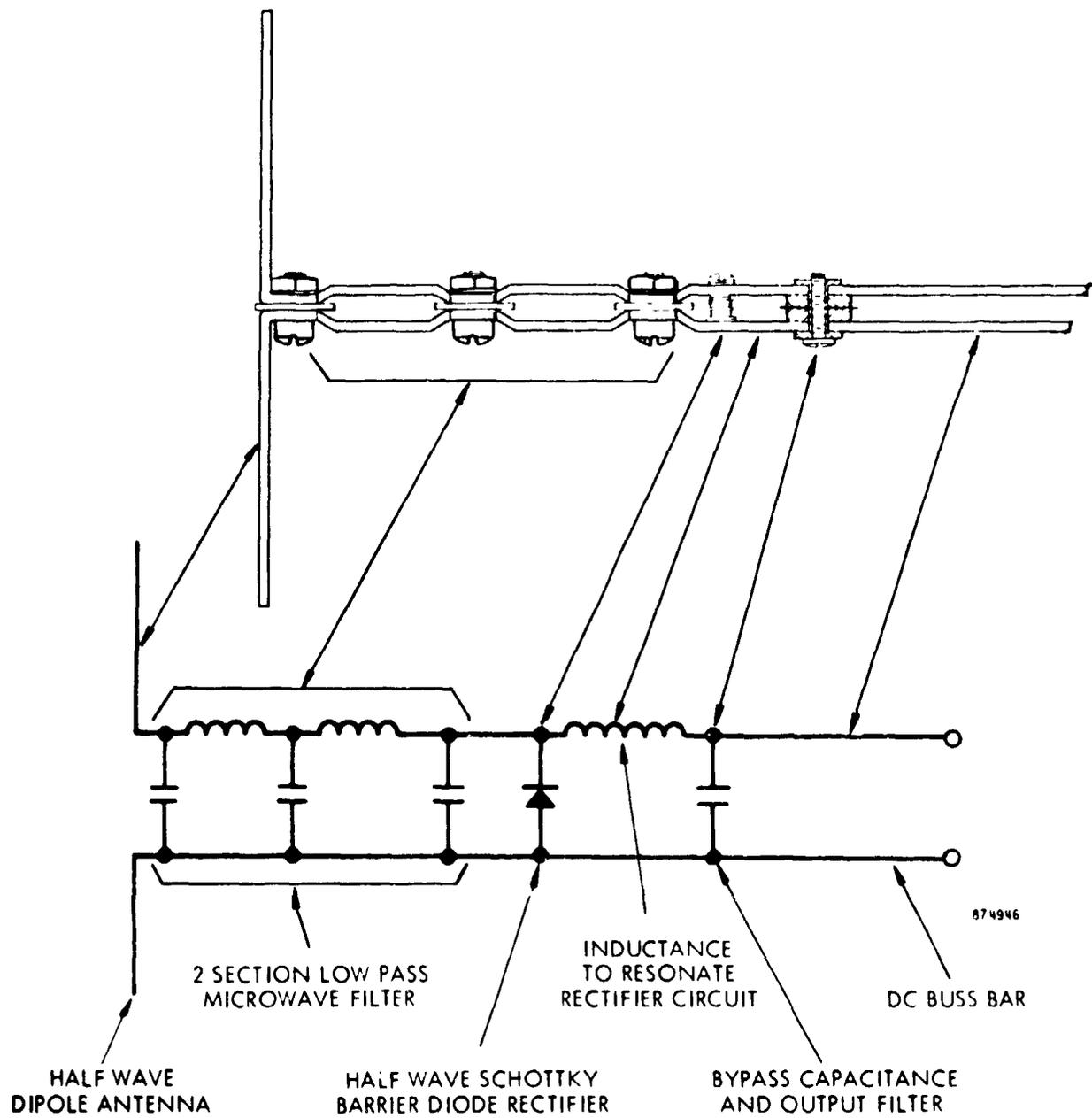


Figure 3-10. Simplified Electrical Schematic for the Rectenna Element.

watts of microwave power per square meter and a rectenna efficiency of 70 percent. A lighter-weight material composed of  $1.27 \times 10^{-3}$  cm (1/2 mil) Mylar and 14.179 m (0.5 oz.) copper is also available; this would halve the mass for the lower power densities where the copper cross section would then be adequate for lower DC power output densities. The use of aluminum rather than copper as conductors would further reduce the mass for a given conduction loss and heat transfer capability. Even further weight reduction would be possible in those applications in which the DC power load requirement takes place at high voltage for a given power level and in space applications where power densities may be low while physical strength is of negligible importance.

With respect to the construction of the thin-film printed-circuit, cost and complexity can be minimized by using a uniform thickness of film and limiting the circuitry to the two sides of the thin-film, preferably without interconnections between the two sides. To accomplish this objective it was necessary to resolve a number of conflicting demands, which can be best understood by reference to Figure 3-10 which shows a simplified electrical schematic circuit diagram of the rectenna element in the physical form that it has been developed. As shown in Figure 3-10, the input consists of a dipole antenna, two input filters which consist of inductances and capacitances, a rectifier circuit involving the diode rectifier, and a capacitor which acts both as a microwave low-impedance bypass in the rectifier tank circuit and as an energy storing element to filter out microwaves from the DC output.

The inductive sections of the network in the conventional format are formed from sections of a bar-type parallel transmission line. The equivalent inductances can be easily formed from a parallel transmission line printed on one side of a Mylar film as shown in Figure 3-11a. The capacitances present more of a problem, particularly so because of the large differences in values needed for the filter network capacitances and the bypass capacitance in the rectifier circuit. The filter network capacitances may be as low as 0.25 picofarad while the bypass capacitance should be at least 10 picofarads and preferably higher.

The capacitances may be simply formed by adding sections of conductive material below the transmission line on the opposite side of the film as depicted in Figure 3-11b. The equivalent circuit thus formed is two capacitances in series. Therefore, if we desire a capacitance of 10 picofarads for the bypass capacitor in the circuit of Figure 3-10, each of the capacitances must be 20 picofarads. To do this in the area that is available implies a small spacing between the two faces of the capacitance and this in turn implies a thin-film of the order of  $1.27 \times 10^{-3}$  cm (0.5 mils) to  $5.08 \times 10^{-3}$  cm (2.0 mils) thick. This then means a much smaller area to achieve the low capacitances needed in the low pass filter network design as shown in Figure 3-11b. The areas are sufficiently small to imply a high degree of accuracy in reproducing the patterns on both sides of the film.

A more attractive way to reproduce a very low value of capacitance is with an interleaving-finger design added to the transmission line configuration. The design is nearly independent of the thickness of the film since the bulk of the capacitance results from air dielectric. However, the fingers have to be too long and too closely spaced for capacitance over 0.25 picofarad, and two of the three

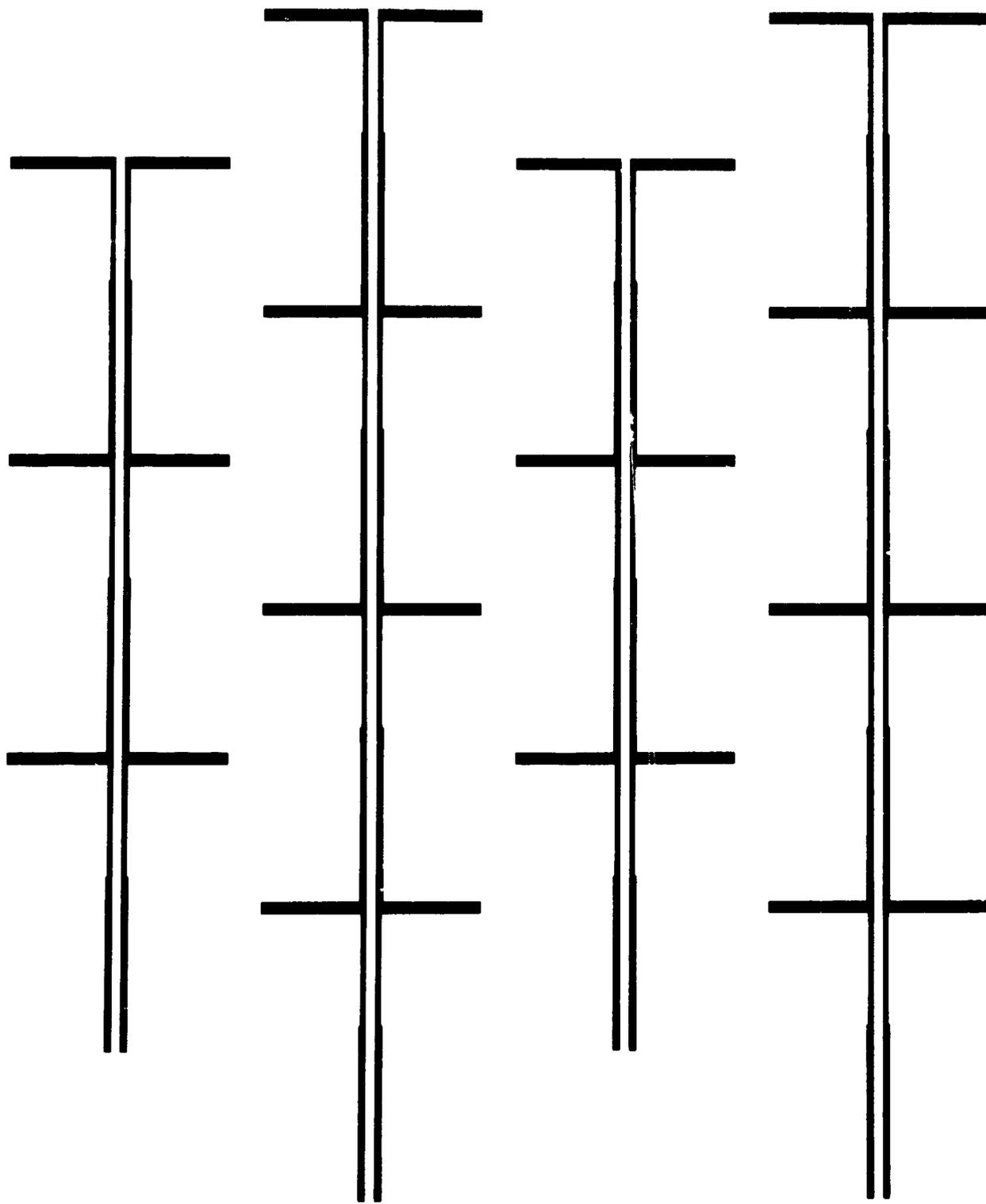


Figure 3-11a. Size Reduced Copy of Photo Mask for Top Side of Thin-Film Printed Circuit Rectenna.

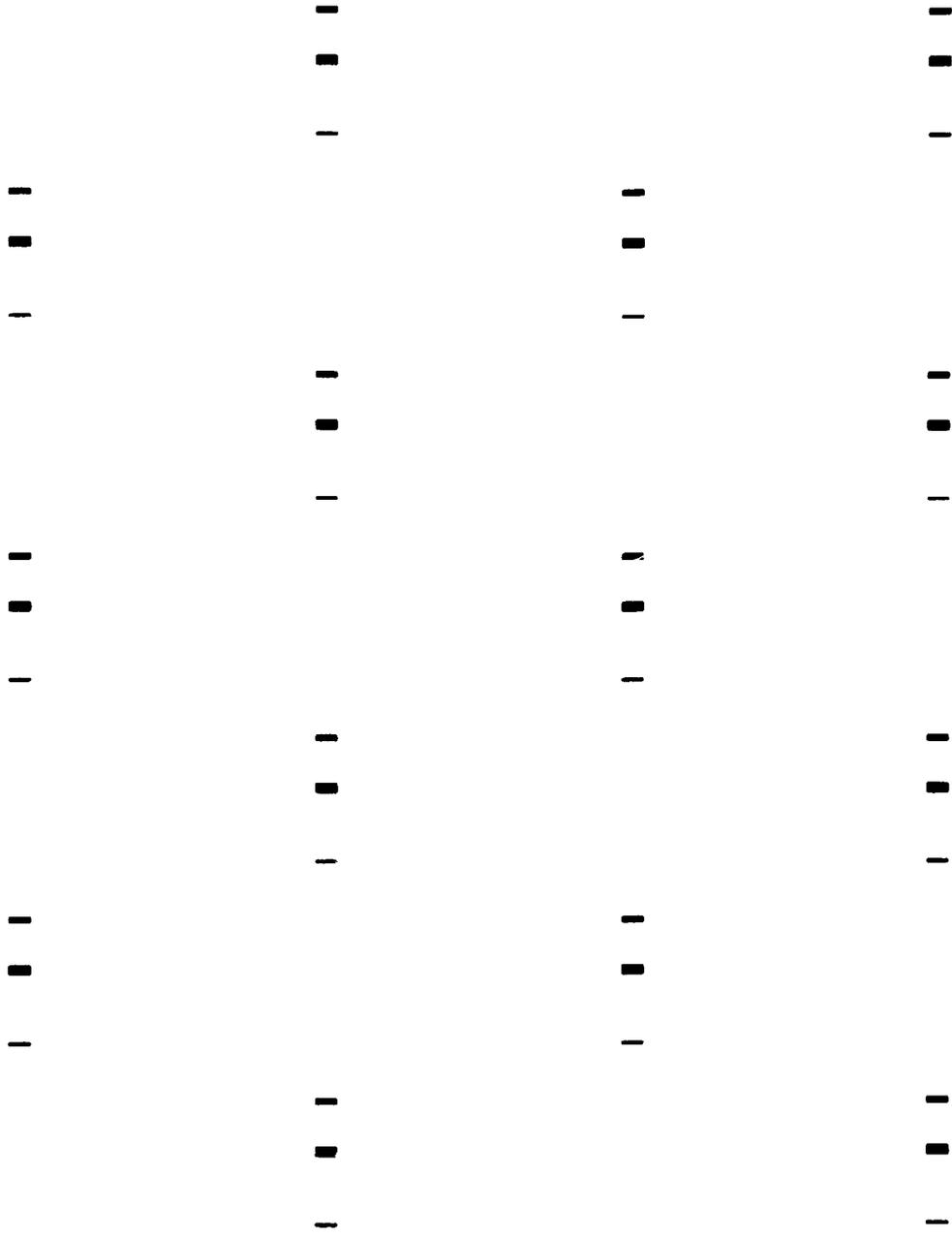
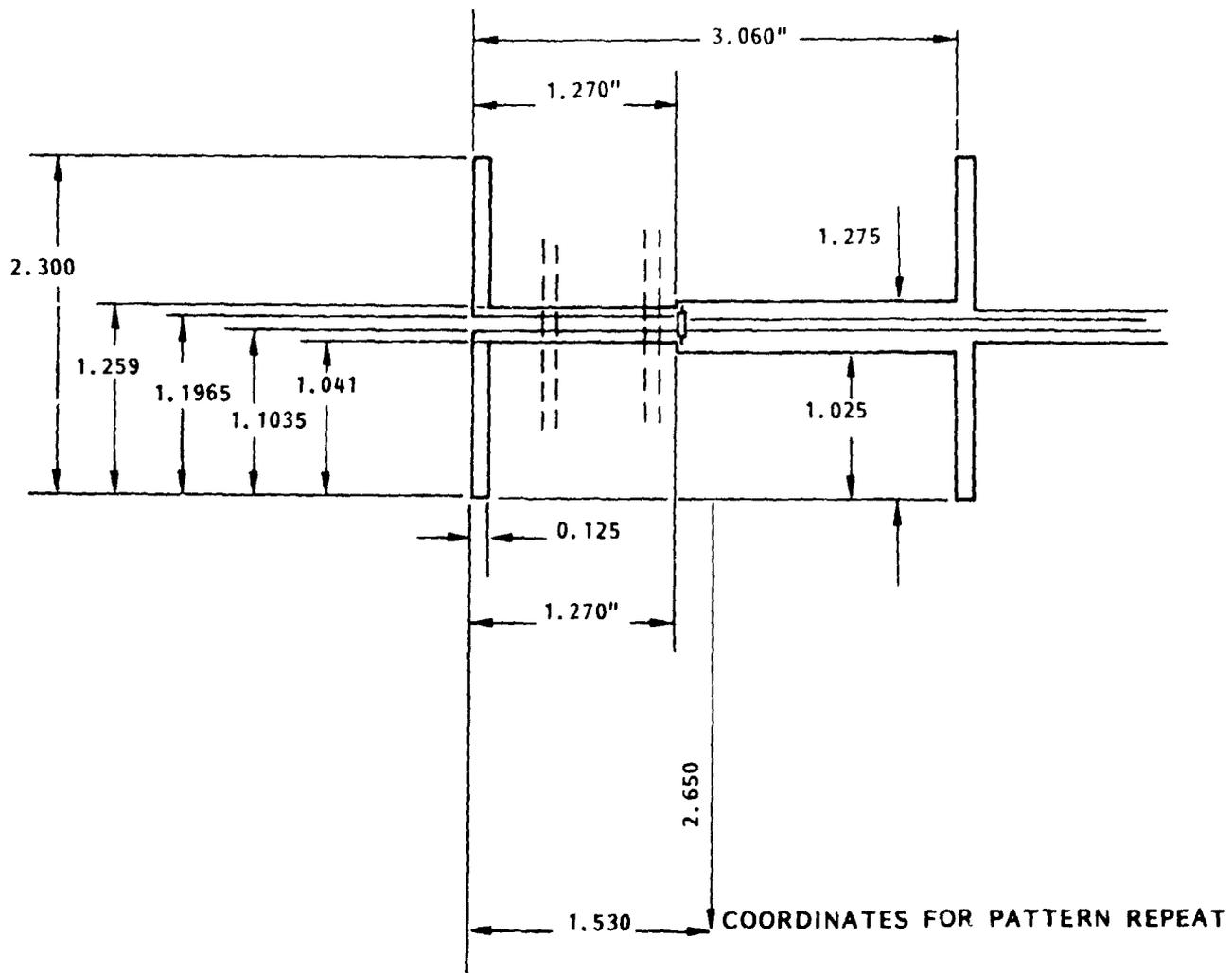
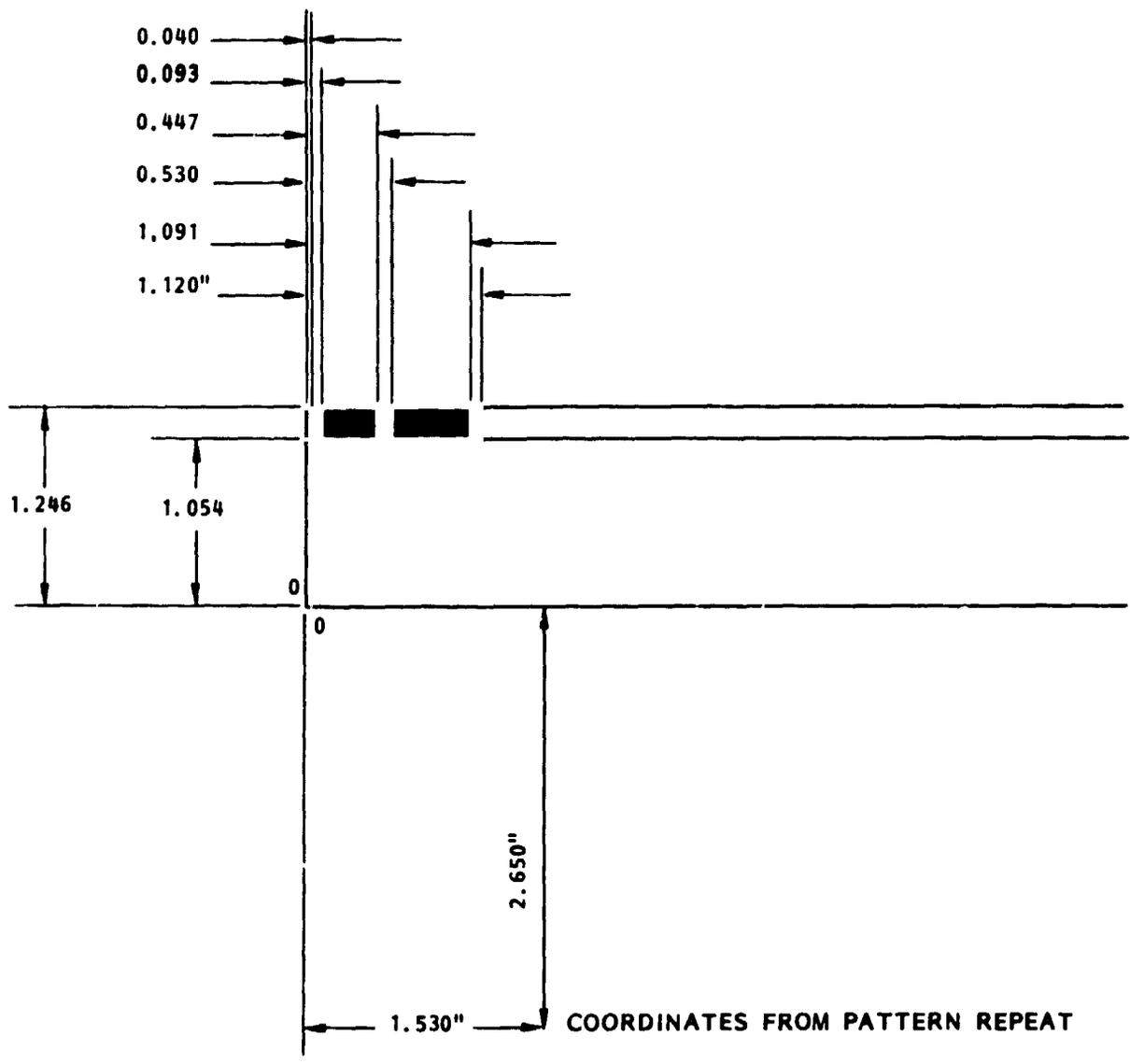


Figure 3-11b. Size-Reduced Copy of Photo Mask for Bottom Side of Thin-Film Printed Circuit Rectenna.



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Figure 3-11c. Dimensions of Layout of Figure 3-11a.



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Figure 3-11d. Dimensions of Layout of Figure 3-11b.

The initial fabrication followed a design in which all the capacitances are formed by imprinting areas of copper on the side of the film opposite the transmission line.

All of the circuit elements of the foreplane are formed by conventional printed-circuit techniques with the exception of the rectifier diode itself. This is separately fabricated and in the initial design consists of a previously designed and tested GaAs Schottky barrier chip housed in the sub miniature D014 glass package. The diode straddles the printed-circuit transmission line and is attached to it by soft solder. Other bonding techniques could be considered.

The pattern coordinates for the etched circuits shown in Figures 3-11a and 3-11b are given in Figures 3-11c and 3-11d, respectively.

#### 3.4 Design of the Electrical Circuit and Physical Layout of the Rectenna Foreplane

The prototype of the design of the rectenna element for the thin-film printed-circuit element is a rectenna element designed to match a high DC resistance load to the typical dipole impedance of 120 ohms. This element is shown in Figure 3-8 and described on pages 56 and 57 of Reference 11. The feature of this element is that the second lowpass filter (as observed looking in from the dipole antenna terminals) acts as an impedance transforming element so that the normal 120 ohm impedance at the output of the first lowpass filter is transformed into an impedance that matches the rectifier circuit when an approximate 400 ohm load is attached to it. The efficiency of this rectenna element was measured as high as 86 percent with a one-watt microwave power input.

To adapt the design of Figure 3-8 to the thin-film, printed-circuit rectenna it was necessary to modify the diode design and to establish an expression for the characteristic impedance of the transmission lines in the physical form of a printed circuit.

It is necessary to know this impedance for design purposes because the equivalent inductance values for a section of transmission line depend both upon its length and its characteristic impedance. Two expressions were developed by Dr. Robert Kuhl, a consultant. One expression is for  $a/b < 0.3$  where  $a$  is the spacing between the conductors and  $b$  is the overall width of the transmission line.

The expression follows:

$$Z_0 = \frac{377\pi}{4 \log_e 2 \sqrt{\frac{b}{a}}} \quad (3-1)$$

The other expression is for  $a/b > 0.1$  to  $a/b = 1$ .

The expression follows:

$$Z_0 = \frac{377}{\pi} \log_e 2 \left( \frac{1 + \sqrt{a/b}}{1 - \sqrt{a/b}} \right) \quad (3-2)$$

These relatively simple formulas are better than one percent accurate in their range. Either formula can be used in the overlap region.

An expression was also developed for the capacitance between interleaved fingers in which one set of fingers is attached to one side of the transmission line and the other set attached to the other side of the transmission line. This expression is given below

$$C = \frac{\pi \epsilon}{2 \ln \left( 2 \cot \frac{\pi}{4} \frac{f}{f + d} \right)} \quad (3-3)$$

where:  $\epsilon = \frac{1}{36\pi} \times 10^{-11}$  farads per centimeter

$d =$  spacing between fingers

$f =$  width of each finger

This expression was useful in investigating the possibility of achieving the necessary values of filter capacitance with a printed circuit on one side of the film only, as previously discussed.

The electrical design of the filters is based upon classical two-terminal-pair network theory where it is assumed that each filter section is terminated in its own characteristic impedance. Furthermore, the simplest type of low-pass filter is used, the "constant k" type. It was found in our previous work that these filter sections have small insertion loss, of the order of one percent per section, and are considerably more efficient than filters designed with more complex approaches such as the Tchebycheff filter. It should be pointed out that most filters are designed to give fast attenuation at the band edge but, in the rectenna application, the first frequency where attenuation is needed is the second harmonic or twice the frequency of the input signal.

The filters are designed so that the phase shift through them is approximately  $90^\circ$  at 2.45 GHz. Such a section has impedance transforming properties such that

$$Z_i = \frac{Z_o^2}{Z_T} \quad (3-4)$$

where  $Z_i$  is the input impedance to the filter

$Z_o$  is the characteristic impedance of the filter section

$Z_T$  is the terminating impedance.

If the terminating impedance is a resistance, then the input impedance will also be a resistance whose value is given by the above expression.

Symmetrical filter sections can be of a T or  $\pi$  format. We have utilized the  $\pi$  or mid-shunt format for the filter section. With this format it is easier to work with admittances than impedances.

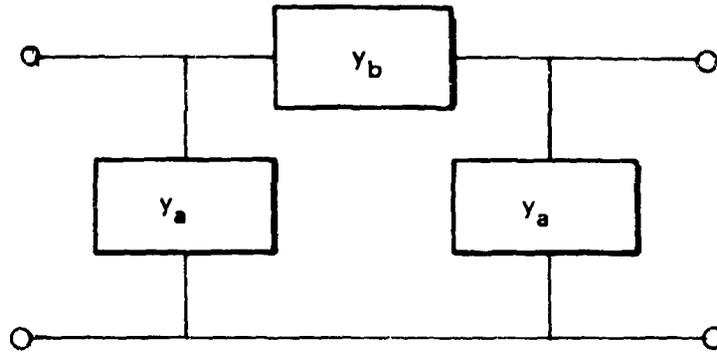


Figure 3-12a.

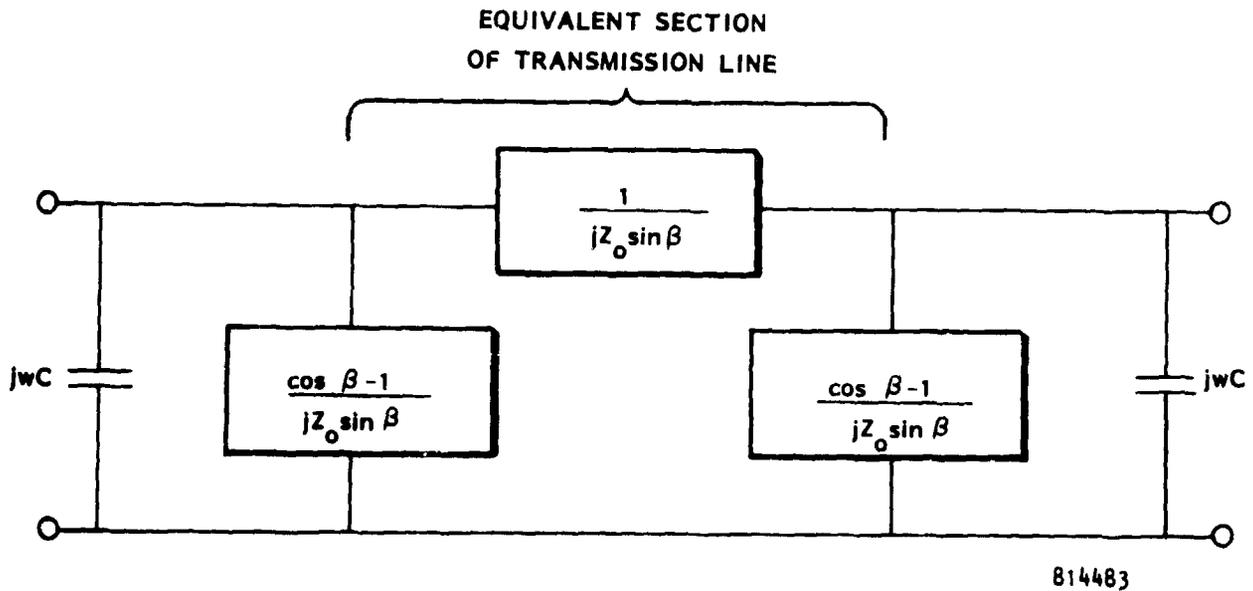


Figure 3-12b.

General Network Parameters for Low Pass Filter.

The general format of the  $\pi$  network section is shown in Figure 3-12a. Figure 3-12b relates the general format of 3-12a to the specific elements of the filter network with which we are directly concerned. The section of transmission line which behaves at low frequency as an inductance (as shown in Figure 3-11) is represented by the  $\pi$  section of equivalent lumped circuit elements in Figure 3-12b. The circuit elements are functions of the frequency as implied by the parameter,  $\beta$ , which is the electrical length of the transmission line section and is given by

$$\beta = \frac{2\pi\ell}{\lambda} = \frac{2\pi\ell f}{c} \quad (3-5)$$

where  $\ell$  = physical length of line section  
 $\lambda = \frac{c}{f}$   
 $f$  = frequency  
 $c$  = velocity of light

The representation as shown in Figure 3-12a holds at all frequencies so that the filter section has a series of pass and stop bands. We are primarily concerned with its behavior in the lowest pass band. The characteristic admittance and phase functions of Figures 3-12a and 3-12b are respectively given by:

$$y_o = \sqrt{y_{11}^2 - y_{12}^2} \quad (3-6)$$

and 
$$\theta = \cos^{-1} \frac{-y_{22}}{y_{12}} \quad (3-7)$$

where 
$$y_{11} = y_a + y_b = y_{22} \quad (3-8)$$

$$y_{12} = -y_b \quad (3-9)$$

With the use of Figure 3-12,

$$y_{11} = j\omega C + \frac{\cos \beta - 1}{j Z_o \sin \beta} + \frac{1}{j Z_o \sin \beta} = j\omega C + \frac{\cos \beta}{j Z_o \sin \beta} \quad (3-10)$$

$$y_{12} = -\frac{1}{j Z_o \sin \beta} \quad (3-11)$$

Then

$$y_o = \sqrt{y_{11}^2 - y_{12}^2} = \sqrt{\left(j\omega C + \frac{\cos \beta}{j Z_o \sin \beta}\right)^2 - \left(\frac{-1}{j Z_o \sin \beta}\right)^2} \quad (3-12)$$

in which  $Z_0$  is the characteristic impedance of the section of transmission line.

Now, if the assumption is made that the filter is designed for  $90^\circ$  phase shift, from equation (3-7) we have

$$-wCZ_0\sin\beta + \cos\beta = 0 \quad (3-13)$$

from which  $\cot\beta = wCZ_0$  (3-14)

If expression (3-14) for  $\cot\beta$  is substituted into (3-12), we obtain

$$Y_0 = \sqrt{w^2 C^2 + 1/Z_0^2} \quad (3-15)$$

At this juncture it is noted that there are two input filter sections which have different values of  $Y_0$ , which are denoted as  $Y_{01}$  and  $Y_{02}$  for the section nearest the antenna and the farthest from it, respectively. For these two sections we have selected values of 0.00833 mho for  $Y_{01}$  and 0.00555 mho for  $Y_{02}$ , corresponding to characteristic impedances of 120 and 180 ohms, respectively.

It is now necessary to specify the network elements which are the lumped capacitances, the characteristic impedance,  $Z_0$ , of the section of transmission line and the length of the transmission line. A value for  $Z_0$  that seems to be consistent with the requirements imposed by physical constraints and equation (3-1) is 270 ohms. A frequency of 2.45 GHz is assumed for the frequency at which the phase shift through the network is  $90^\circ$  and which therefore enables the use of equation (3-14) and (3-15). When the value of 270 ohms for  $Z_0$  is inserted into equation (3-15) for the values of  $Y_{01}$  and  $Y_{02}$  which have been selected, we find values for the filter capacitances of 0.48 and 0.269 picofarads.

With the shunt capacitances of the filter determined, and paired with a characteristic impedance  $Z_0$  of 270 ohms for the transmission line, the phase shift  $\beta$  along the section of transmission line and therefore the length of the line segment is determined from equation (3-14). The phase shift for the first filter section is  $26.4^\circ$  corresponding to a line length of 0.899 cm (0.354 in.) and the phase shift for the second filter section is  $41.84^\circ$  corresponding to a line length of 1.427 cm (0.562 in.).

The electrical circuit that has just been developed is shown schematically in Figure 3-13. The adjacent capacitors in the two filter networks are combined in the physical circuit. The distance,  $l_1$ , is arbitrarily set at 0.406 cm (0.160 in.), a dimension preserved from that of the rectenna element in Figure 3-4. The distance,  $l_2$ , is experimentally determined for the best match of the load resistor,  $R_L$ , to the antenna. This distance was tentatively determined from the experimental data of Figure 3-6 to be 0.70 cm. From a circuit point of view, the length of the transmission line between the diode and  $C_3$  serves as an inductance to resonate the capacitance of the diode. However, the best match to the dipole antenna may occur slightly off resonance.

From equation (3-4) the terminating impedance that matches the system, in which  $Z_i$  is 120 ohms and  $Z_0$  is 180 ohms, is 270 ohms. This is the impedance looking into the rectifier circuit. The load resistance is usually higher than this in the ratio of 1.3 to 1.4.

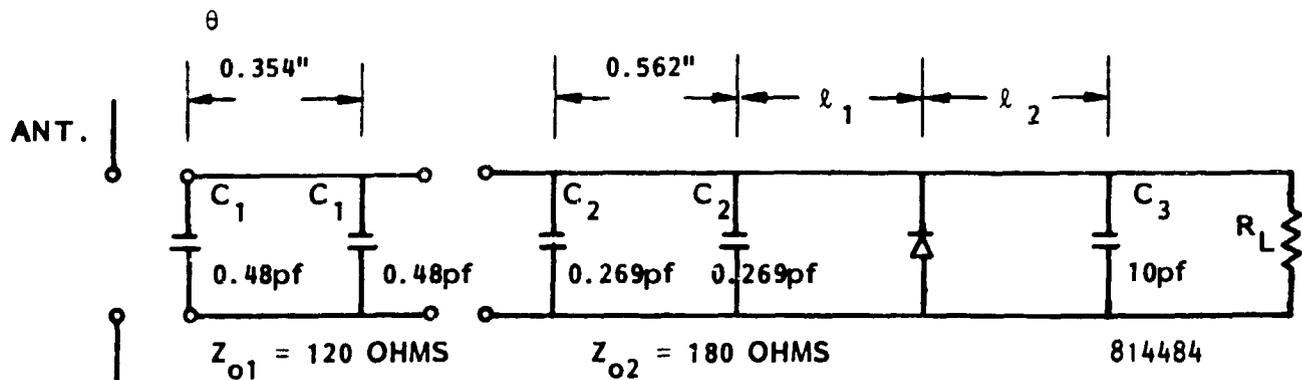


Figure 3-13. Nomenclature and Values of Circuit Elements in the Thin-Film Printed-Circuit Rectenna Element.

### 3.5 Design, Construction and Checkout of the Special Diodes

A particular type of diode must be used for this application. It is necessary that it be capable of operating at high temperatures to permit the conductors to which it is attached to radiate waste heat into an environment with an elevated ambient temperature. The internal temperature drop should be as low as possible. The efficiency should be as high as possible. It should be packaged in such a way that it can be easily fitted to the thin-film printed circuit.

The plated heat-sink GaAs Schottky barrier diode with carefully controlled thickness of the epitaxial layer and packaged in a DO14 miniature glass package meets these requirements.

A considerable amount of successful experience with such diodes in a ceramic package has been accumulated. The application of such diodes on a fairly large scale basis was the 30-kilowatt rectenna tested on the Mojave Desert.<sup>12,13</sup> Life test on 180 such diodes in rectenna elements that were operated at no more than 6 watts of DC power output produced no failures in over 600,000 diode hours of operation. (Page 74 of Reference 11).

The construction of the layer diode is shown in Figure 3-14. The Schottky barrier is the platinum interface with the "N-type region" as shown in Figure 3-14. The N-type epitaxial layer is a layer of GaAs doped with impurities to provide a reverse breakdown voltage of about 45 volts. The impurity level also establishes the resistivity of the epitaxial layer and current flow through it represents a loss and heat is generated. The layer is therefore kept as thin as possible consistent with the requirement that there is no "punch-through" effect to compromise the value of reverse voltage breakdown.

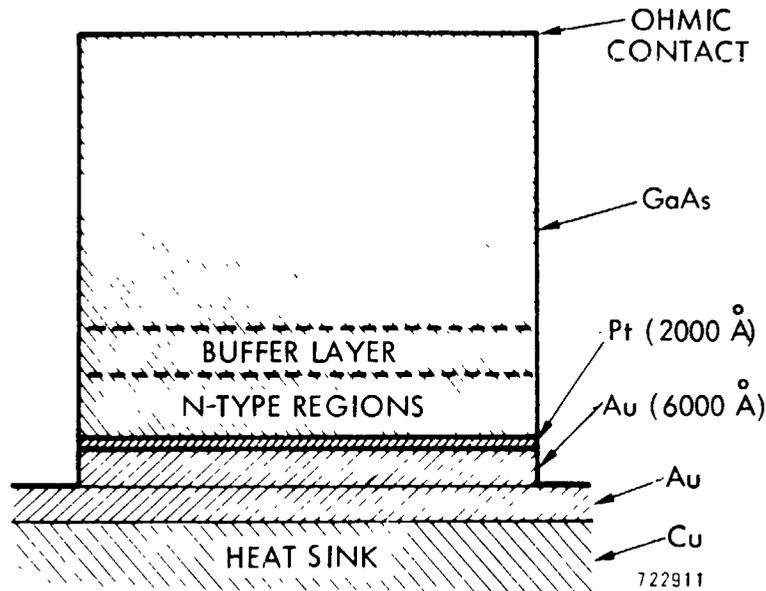


Figure 3-14. The Special Construction Used in the Plated Heat-Sink Diode to Minimize Temperature Rise Within the Diode.

To carry the heat away as efficiently as possible, the platinum is plated first with gold and then with copper. The bulk GaAs is also ground to a thin dimension to cut down ohmic losses in the bulk material although this is not a serious contributor to losses and heat generation.

A special lot of 10 experimental GaAs Schottky barrier diodes in the miniature glass package D014 were fabricated. One of these diodes was checked in the rectenna element format shown in Figure 3-8. The values of efficiency that were obtained at various power levels is given in Figure 3-9. The efficiency is the ratio of DC power output to the power actually absorbed by the rectenna element. However, the percentage of power reflected was low, as shown in Figure 3-8. The measured efficiency was within three percent of that obtained with the Schottky barrier diode in the original ceramic package.

### 3.6 Heat Dissipation of the Thin-Film Printed-Circuit Rectenna

The thin-film printed-circuit rectenna can dissipate a considerable amount of power by conduction through and radiation from the printed circuit. If this is combined with a diode that has a low internal thermal resistance, high efficiency, and an ability to operate at high temperature, the result can be DC power output in the region of one watt per diode without any convection cooling which would be available as an additional aid to heat dissipation in many instances.

The analysis that will be outlined in this section is incomplete in the sense that all radiative surfaces and all conductive paths have not been included because of the overall complexity of such an analysis. If these are considered, the dissipative capability will be greater than this analysis will predict. Specifically neglected was (1) any flow of heat into and radiation from the exposed Mylar, and (2) any flow of heat from the diode in the direction of the low pass filters. It was also assumed that the flow of heat from the ohmic contact side of the diode was negligible.

The flow of heat and its radiation may be best studied by a computer program which breaks up the conduction and radiative path in small sections and computes the radiation losses from each section and the incremental increase in temperature from one end of the segment to the other occasioned by the flow of heat passing through the segment. To apply such a program, it is necessary to start at the outboard end of the radiative segment and make an assumption as to the temperature of the end segment and its relationship to the ambient temperature. The radiation losses are given as:

$$\text{Radiated Power} = (5.67 \times 10^{-2}) (\epsilon) (T_2^4 - T_1^4) \text{ watts/cm}^2$$

where:  $5.67 \times 10^{-12}$  watts  $\text{cm}^{-2}$   $\text{K}^{-4}$  is the Stefan-Boltzmann Constant

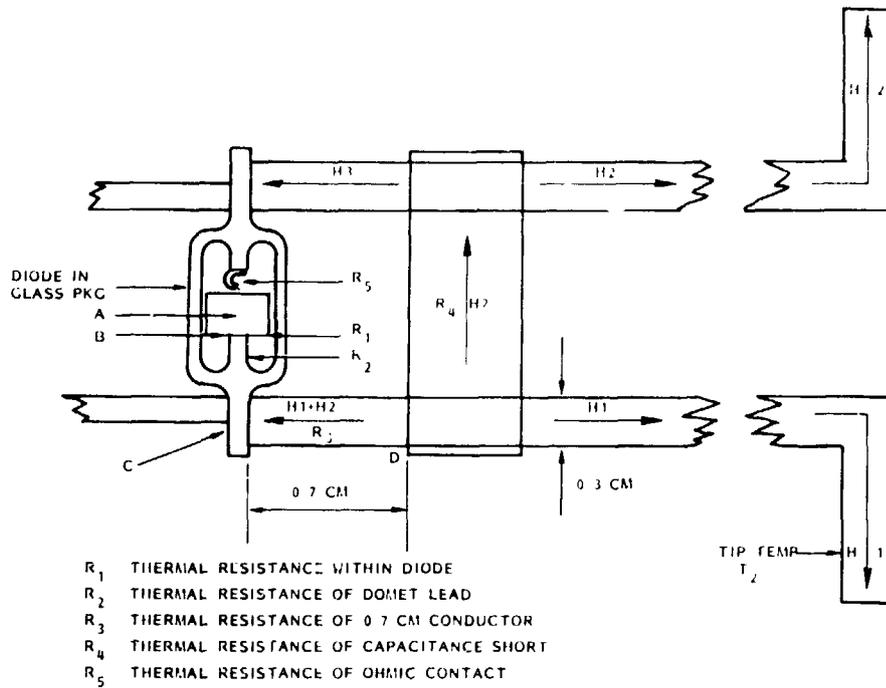
$\epsilon$  is the emissivity

$T_2$  is the temperature in degrees Kelvin of the radiative surface

$T_1$  is the ambient temperature.

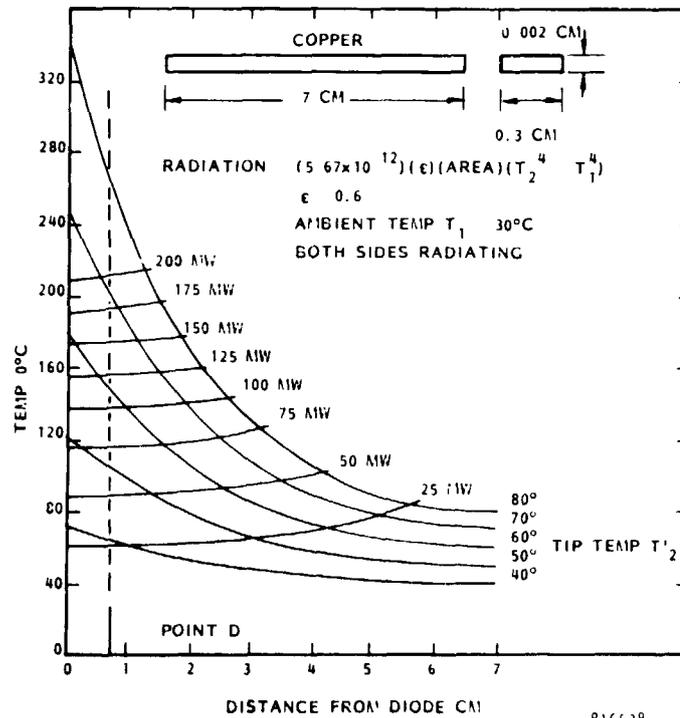
For our purposes we will make the assumption that the copper conductor surface can be treated to have an emissivity of 0.6, which also implies an absorptance of the same amount at the same wavelengths if the  $(T_2^4 - T_1^4)$  relationship is to hold. The ambient temperature is assumed to be 30°C or 303°K, set by the Earth and the cloud albedo on a hot day. It is assumed that the rectenna for an atmospheric platform will never look at the sun and that it will be protected from the sun on the backside by a metallic ground plane that was a high reflectivity for the sun's spectrum but a high emissivity for the radiation of heat at wavelengths corresponding to the ambient temperature. It is also assumed that the copper conductor will radiate from both front and back sides, thus doubling the radiation area.

The flow of heat is assumed to be from the diode along the conduction path to one of the dipole antenna legs in the direction away from the microwave input filters, shown as H1 in Figure 3-15. Calculations of total heat radiated and temperature rise along the path have been made for a set of end temperature,  $T_2$ , of 40°, 50°, 60°, 70° and 80° Centigrade. The rise in temperature as a function of distance along the path for these various end temperatures is shown directly in Figure 3-16. In Figure 3-16, the heat flow path is extended back to the diode. Contours of radiated power are also plotted in Figure 3-16. With the use of the data, both the temperature of the conductor at a point and the power that has been radiated by the conductor by its surface to the outboard side of the point may be obtained.



816537

Figure 3-15. Schematic Showing Heat Flow from Diode.



816538

Figure 3-16. Temperature Rise and Heat Dissipated in Copper Conductor as Function of Distance from Tip of Dipole Antenna. (See Figure 3-15).

An interesting discovery of fortunate consequence in the heat dissipation analysis is that, while only one of the conductors that leads to the dipole antenna is directly connected to the diode, both conductors effectively dissipate heat. This is because of the presence of the large electrical capacitance that is used as an electrical short in the rectifier circuit. Although the thermal conductance of Mylar is only  $4 \times 10^{-4}$  calories/sec/cm<sup>3</sup>/°C the comparatively large area and the thinness of the Mylar gives an effective thermal resistance of only 10°C/watt.

Hence, at the point "D" on Figure 3-16 that corresponds to the position of the electrical short, (about 0.7 cm from the diode) the power radiated is nearly double that shown.

It is now necessary to consider the additional thermal drops that occur between the point D and the highest temperature point in the diode itself. Figure 3-15 shows the additional thermal points, A, B, C, and the thermal resistances,  $R_1$ ,  $R_2$  and  $R_3$ , that occur between these points.

- A - The hottest point in the diode which controls the power level at which the diode can be operated.
- $R_1$  - The thermal resistance between point B & A. For the plated heat-sink GaAs diode that is being used, it is 40°C/watt.
- B - The point at which the Dumet lead attaches to the internal diode.
- $R_2$  - The thermal resistance between point C and B that is caused by the Dumet lead. This is estimated to be 106°C/watt.
- C - The point at which the Dumet lead joins the external copper conductor.
- $R_3$  - The thermal resistance of the 0.7 cm long copper conductor between the points D & C. It is 279°C/watt.

In total,  $R_1$ ,  $R_2$  and  $R_3$  add up to 425°C/watt.

Of these three thermal resistances,  $R_1$  and  $R_2$  have no radiation of consequence associated with them.  $R_3$  does have appreciable radiation associated with it. However, this additional radiation will be neglected for the moment.

In Figure 3-17, H1 and H2 are assumed equal and added together at point D. Then the hottest point in the diode is obtained by adding in the combined thermal resistance of 425°C/watt of  $R_1$ ,  $R_2$  and  $R_3$ . The thermal drop is seen to be very substantial, particularly between points C & D.

The additional heat disposal and additional temperature rise in the region C to D when heat radiation is added in is shown for two cases in Figure 3-17 by the dotted lines.

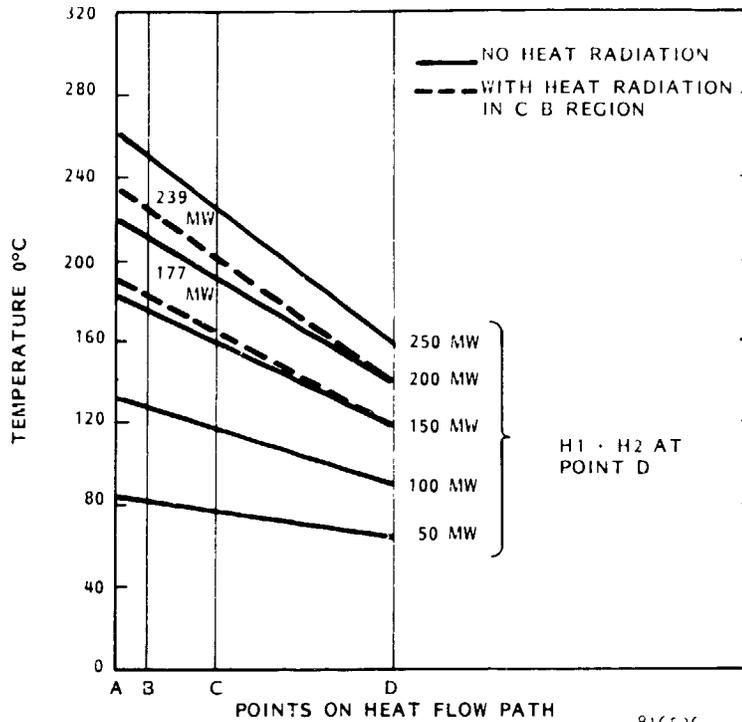


Figure 3-17. Additional Temperature Rise within Diode and Short Conductor Lead to Branching Point for H1 and H2 Heat Flow (see Figure 3-15)

### 3.6.1 Discussion of Results of Heat Dissipation Analysis

As previously noted, the power dissipated for a given temperature rise in the diode is greater than Figures 3-16 and 3-17 indicate. It may be greater by as much as 25 percent, so the data in Figures 3-16 and 3-17 are conservative.

It is not expected that the diode losses for operation in the region of one watt will be greater than 15 percent. Hence, for one watt of DC output, the temperature in the diode should stay below 200°C. At 200°C, the diode lifetime is expected to be at least 10,000 hours.

The dissipation could be increased greatly by operating with increased conductor cross section to reduce temperature drops. Doubling the conductor cross section and increasing the radiation of the dipole antenna by making it on the form of a "bow tie" could nearly double the dissipation for a given diode temperature.

Finally, convective cooling of the conductors could be used in many of the applications and this would greatly increase the dissipation rating.

### 3.7 Method of Layout and Fabrication of the Thin-Film Printed-Circuit; Rectenna Mechanical Dimensions

Once the mechanical dimensions of the design are established, it is possible to invoke the use of a procedure used at Raytheon to make printed circuits. The method uses the numerical control of a machine that can accurately lay out a photographic mask to within  $\pm 2.54 \times 10^{-3}$  cm ( $\pm .001$  in.) of the proposed design. The dimensions of the design are stored in a magnetic tape that controls the making of the mask.

Two masks are required -- one for each side of the Mylar film. The close registration that is required in the use of these plates is obtained by the visual line up of cross hairs which are also imprinted on the masks. See Figures 3-11a and 3-11b for the appearance of the masks.

One of the advantages of this general approach to our application in which the same mechanical pattern is reproduced over and over again, is that the mechanical dimensions of the rectenna element need to be put into the system only once. Only dimensional coordinates for the reference points of the repetitive pattern need to be additionally inserted. The number of circuit elements that can be included on a single mask are limited only by the area capacity of the numerically controlled layout machine.

In the development of the thin-film printed-circuit rectenna, it will be necessary to make at least one repetitive cycle of the layout process because it is necessary to establish the optimum location of the bypass capacitor in the rectification circuit by a moveable capacitance. The bypass capacitance noted as  $C_3$  in Figure 3-1, is omitted from the first layout. Its position is established experimentally by a sliding short arrangement shown in Figure 3-4. Its location is not highly critical and once the location is established the capacitor can become part of the printed circuit.

### 3.8 Design Options for Combining the Foreplane and Reflecting Plane of the Rectenna

In the foregoing sections we have been primarily concerned with the design and testing of the rectenna foreplane. From an electrical design, mechanical design, thermal control, and fabrication point of view it is the dominating portion of the rectenna. However, a rectenna must have a reflecting plane to allow it to approach 100 percent in collection efficiency. Without it, the maximum collection efficiency is 50 percent.

The reflecting plane can have very low mass. All that is needed is a metallic film about  $2 \times 10^{-4}$  cm (0.08 mil) thick. Made from aluminum, such a film would have a mass of 5.6 grams per square meter. It could be applied to a Kapton or Mylar film no greater than  $1.27 \times 10^{-3}$  cm (0.5 mil) thick which would have a mass of 18 grams per square meter. If an additional 26 grams is added for the separators and contingencies, a budget of 50 grams is established.

The major design problem is to combine the foreplane and the reflecting plane with a separation of about 2.54 cm between them. A tolerance of  $\pm .254$  cm would probably be satisfactory. There are a number of possible options, none of which has been experimentally carried out.

One option is to separate the two by gas pressure using threads or film under tension to maintain the separation. The gas could also be used for convective cooling if it were circulated between the foreplane and reflecting planes. Helium is an outstanding convective cooling gas.

Another option is to separate by bonding both foreplane and reflecting plane to foam material. Although continuous foam in the sandwich would be quite massive, a large amount of it could be cut out and it would still adequately separate the foreplane and reflecting plane. There are probably other approaches that would be of interest and even come to the forefront once work was started on the obvious ones just discussed.

### 3.9 Load Matching and Bussing of the DC Power

As explained in Section 3.3 the DC power is collected from the individual elements through the printed circuit conductors. In the present approach, the power flows in from the periphery of the array to a central buss as shown in Figure 3-18. Because of the circular format of the array, the various collecting areas have to have different lengths. But it is essential that each string of rectenna elements operate at an optimum efficiency and deliver the amount of voltage to the central buss. This is accomplished as shown in Figure 3-19 by a series-parallel combination of the rectenna elements. If the illumination is uniform, there will be the same number of sections in series to produce the desired DC voltage for the system load. In a long section of line corresponding to Nos. 9 or 10 in Figure 3-18, each section of diodes in parallel will contain more diodes than sections 1 and 2.

The  $I^2r$  loss in the conductors attached to the rectenna elements may be easily computed. The conductor length and cross section in the rectenna element design discussed in Section 3-4 may be used as an example. The loop resistance per meter length of the copper conductor of average width, 0.257 cm, and thickness, 0.002 cm, is 0.566 ohms. However, because the power is collected uniformly over its length and flows in one direction, the effective resistance is only 33 percent of this or 0.189.

The ratio,  $k$ , of the  $I^2r$  loss to the power collected by the string is dependent upon the power,  $w$ , picked up by each element, the number of elements,  $n$ , per unit length, and the length,  $2L$ , of the string, the voltage,  $V$ , of the output, and the effective loop resistance,  $r$ , per meter as follows:

$$k = \frac{4wnrL^2}{V^2} \quad (3-16)$$

It should be noted that the length of the string is  $2L$ , or twice the length,  $L$ , from the center to the edge of the rectenna because the series connection procedure requires an outgoing line as well as an in-going line.

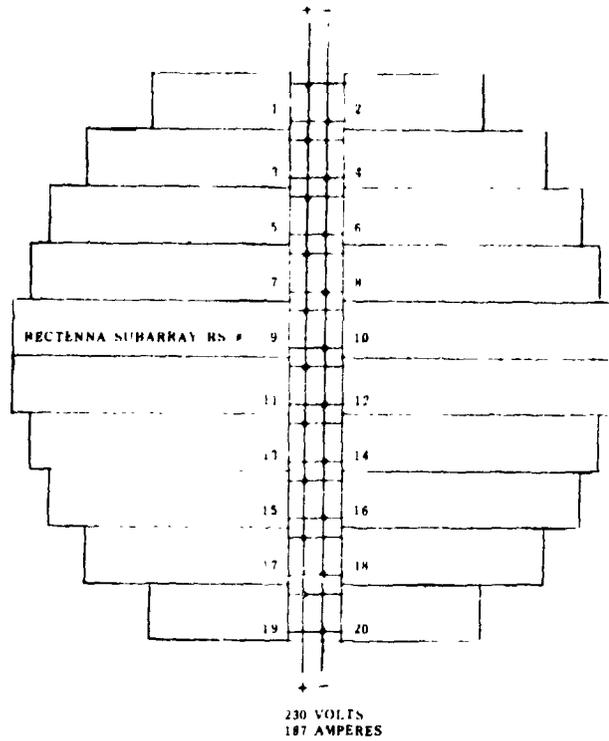


Figure 3-18. The Rectenna is divided into a number of subarrays each of which has a nominal voltage output of 230 volts when the array is being operated at the full 43 kilowatt output level.

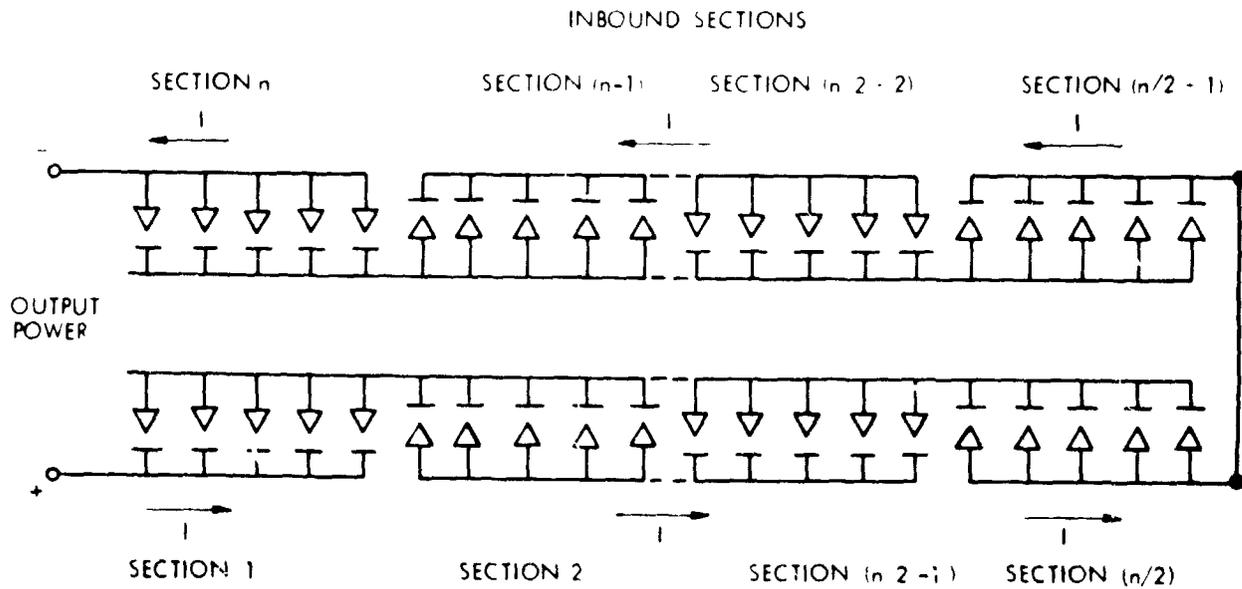


Figure 3-19. Schematic electrical drawing showing how the sections of parallel diodes are connected in series to build up to the desired voltage level at the output.

For the baseline design, L is defined as the distance from the center collecting buss to the outer edge of the rectenna, and it is also the radius of the circularly-shaped rectenna. Also for the baseline design,<sup>7</sup> w = 0.65 watts, n = 13.3, L = 9.91 meters, r = 0.189 ohms, and V = 230 volts. Inserting these values into (3-16) gives a value of k equal to 0.012. Thus, the I<sup>2</sup>r loss for the maximum string length and maximum DC power per unit element is a small part, less than 2 percent of the power collected. As expression (3-16) indicates the loss will be less for shorter string lengths and for lower power output per element.

If the same rectenna structure is made large in diameter and operated at the same power density level and voltage output, k becomes larger. For example, the spheriod geometry proposed in Appendix A, which has the same displacement as the conventional geometry, can support a rectenna 40.84 meters (134 feet) in diameter, or roughly two times as large. The ratio, k, for this rectenna would increase to about 4.8 percent. An increase in conductor thickness might be desirable in this case and such thickness would also decrease the temperature drop in the critical C-D region described in Section 3.6.1. A doubling of the copper thickness would add 30 grams per square meter to the weight.

At the 0.65 watt DC power output level, the DC voltage output at the rectenna element terminals would be in the 15- to 20-volt range. So the number of sections in series would be somewhere between 12 and 15 to satisfy the 230-volt requirement.

It is of interest to note that if the voltage level were increased to 3000 volts, a level consistent with some applications, the I<sup>2</sup>r loss would be very low even in long lengths of the collector circuit.

As shown in Figure 3-18, the power flows into a central buss where it is transported to the payload or propulsion units.

To approach the I<sup>2</sup>r loss in the collecting buss, refer to Figure 3-20. If the power density, P<sub>d</sub>, over the collecting area is assumed to be constant, and the collecting voltage, V, is also constant then the current being collected over a distance dx is:

$$dI = \frac{2 y dx P_d}{V} \quad (3-17)$$

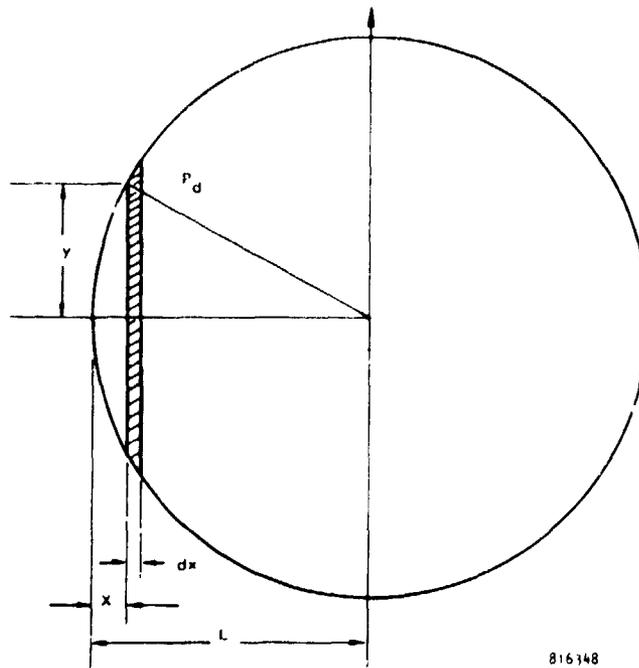
$$\text{but } y = L \sin\theta$$

$$x = L - L \sin\theta$$

$$dx = L \sin \theta d\theta$$

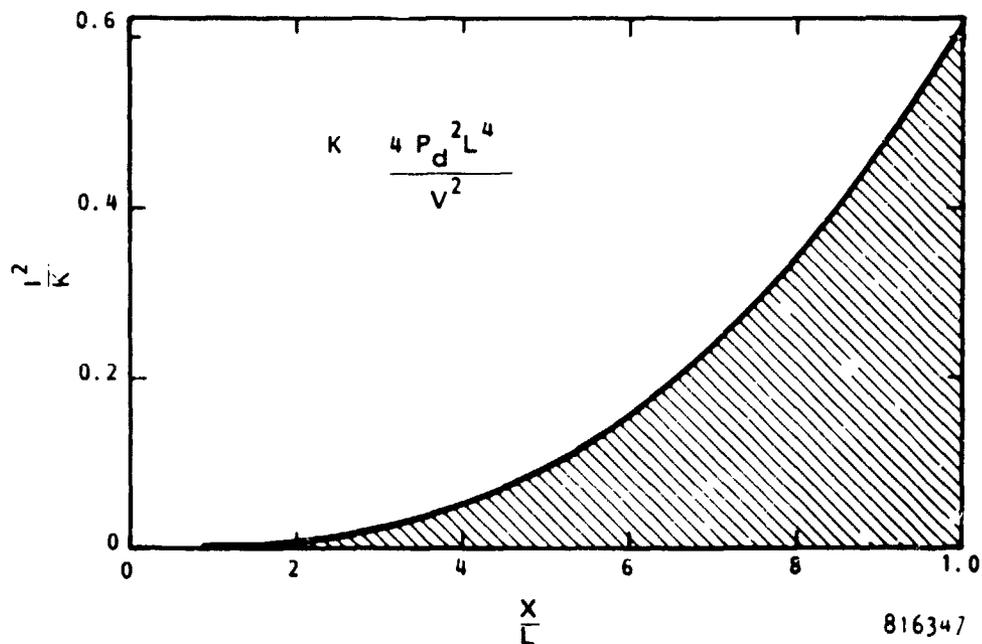
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<sup>7</sup>P<sub>d</sub> = 185 w/m<sup>2</sup> was erroneously used.



816348

Figure 3-20. Geometrical Treatment of the DC Power Collection Along the Diameter of a Circle that is Uniformly Illuminated. The area,  $2y dx P_d$ , represents the increment of power being collected at distance  $x$ .



816347

Figure 3-21. Crosshatched Area Under Curve Represents the  $I^2r$  Loss in a Buss of Uniform Cross Section that is Collecting Power Along a Diameter of a Circle which is Uniformly Illuminated.

and 3-17 becomes

$$dI = \frac{2 P_d L^2}{V} \sin^2 \theta d\theta \quad (3-18)$$

$$\text{and } I = \frac{2 P_d L^2}{V} \left( \frac{\theta}{2} - \frac{1}{4} \sin 2\theta \right) \quad (3-19)$$

$$\text{and } I^2 = \frac{4 P_d^2 L^4}{V^2} \left( \frac{\theta}{2} - \frac{1}{4} \sin 2\theta \right)^2 \quad (3-20)$$

Since  $I^2$  and  $x$  are parametric in  $\theta$ ,  $I^2$  may be plotted as a function of  $x$  as shown in Figure 3-21.

Figure 3-21 may be used to obtain the effective resistance of a buss bar collecting system that has a uniform cross section. If the total current,  $I$ , (equation 3-19) were flowing the entire length of the collecting buss, then the total  $I^2 r$  losses would be proportional to the rectangular area given by the

product of  $\frac{I^2}{K} = 0.62$  and  $\frac{X}{L} = 1.0$ . But the actual loss corresponding to the more gradual build up of current in the buss is the cross-hatched area of Figure 3-21. The effective resistance then is the ratio of these two areas multiplied by the measured resistance of the buss bar. The ratio is approximately 0.26.

If the measured resistance of the buss bar is  $R$ , then the  $I^2 r$  loss will be  $0.26 I^2 r$ . But from Figure 3-21,  $I^2 = 0.62 K$ ,

$$I^2 r = \frac{0.64 P_d^2 L^4 R}{2 V} \quad (3-21)$$

The  $I^2 r$  loss may be expressed as a fraction  $k$  of the DC power collected,

$$\frac{\pi P_d L^2 \eta_r}{2} k = \frac{1.28 P_d L^2 R \eta_r}{\pi V^2} \quad (3-22)$$

when  $\eta_r$  = rectenna efficiency.

Of interest is the mass associated with an acceptable  $I^2 r$  loss, this may be obtained from (3-22) and the following set of relationships

$$R = \frac{2r'L}{A} \quad (3-23)$$

$$m = (2)(A)(L)(\rho) \quad (3-24)$$

where  $r'$  = specific resistance of conductor  
 $A$  = cross-sectional area of conductor  
 $\rho$  = density of the conductor material

Combining 3-22, 3-23, 3-24, a general expression for the mass is

$$m = \frac{(1.63) (r') (L^4) (P_d) (\rho) (\eta_r)}{k v^2} \quad (3-25)$$

If we substitute in values for the baseline design<sup>8</sup> of  $L = 9.9$  meters (990 cm),  $P_d = 185$  watts/m<sup>2</sup> (0.0185 w/cm<sup>2</sup>)  $\eta_r = 0.7$   $r' = 1.8 \times 10^{-6}$   $\Omega/\text{cm}^3$  for copper,  $V = 230$  volts,  $\rho = 8.9$  for copper, we find the mass,  $m$ , is 614 grams. This mass is for one-half the area of the rectenna so total mass is 1228 grams.

If aluminum were used as the buss bar, the mass would be reduced to 600 grams.

Equation (3-25) indicates that if the diameter of the rectenna is doubled, then the mass goes up by a factor of 16 and the collector power goes up by a factor of 4, as well.

3.10 The Estimated Cost of the Completion of the Development of the Thin-Film Printed-Circuit Rectenna and the Construction of a Full-Scale Rectenna Meeting the Requirements of the Reference Design

The development and associated costs were broken down into a series of activities as given below. The uncertainty cost range for each of the activities is also given. The costs are assumed to be in 1980 dollars.

	<u>Estimated Cost</u>	<u>Range</u>
1. Finish up initial development effort on foreplane. This includes two recyclings of the art work, the first to include adding the bypass capacitor, and the second to fine tune the design. Testing would be confined to a single element.	\$10,000	\$7,000 - 13,000

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<sup>8</sup> $P_d = 185$  w/m<sup>2</sup> was used.

	<u>Estimated Cost</u>	<u>Range</u>
2. Finish up development of combined foreplane and reflecting plane and separator. This effort would examine different approaches, decide upon one, and fabricate a small section of the combined array. No electrical testing would be involved.	\$ 7,000	\$ 5,000 - 10,000
3. Fabricate one square meter of the complete rectenna design and test in the pressure and temperature environment typical of 21.336 km (70,000 feet) altitude. A principal portion of this effort would be the testing which would involve the construction of a housing that could be pumped down to the pressures of 21.336 km (70,000 feet) and filled with helium as the environmental gas.	40,000	30,000 - 60,000
<b>Total Development Costs:</b>	<u>\$ 57,000</u>	<u>\$ 42,000 - 83,000</u>
4. Design and fabricate full scale rectenna for reference design:		
Effort Other Than Diode Fabrication	\$117,000	\$ 90,000 - 150,000
Diode Fabrication	<u>350,000</u>	<u>140,000 - 700,000</u>
<b>Total Cost to Fabricate Reference Design</b>	<b>\$467,000</b>	<b>\$230,000 - 850,000</b>

It is obvious from the above cost breakdown that the cost which is least under control is the cost of the diodes for the full scale rectenna. The development item which is the least under control technically is the combining of the foreplane with the reflecting plane and separator.

#### 4.0 THE MECHANICAL INTERFACE OF THE RECTENNA WITH THE VEHICLE

This section deals with the mechanical interface between the rectenna and the vehicle. One of the characteristics of the microwave power transmission system that impacts this interface is that the rectenna has to remain rotationally aligned with the transmitting antenna because of the linear polarization of the system.

Because the conventionally streamlined aerostat vehicle must rotate to head into the prevailing wind, either the ground array must rotate or the rectenna must mechanically rotate with respect to the vehicle. <sup>9</sup>Rotation of the ground antenna would be exceedingly expensive and for this reason probably not practical.

This leaves two options for dealing with the rotational problem in the vehicle. Either the vehicle has an aerodynamic shape that makes it insensitive to the direction of the wind so that it does not have to rotate, or the rectenna can rotate with respect to the vehicle.

The latter arrangement was the first approach investigated to solve this problem. Figure 4-1 shows an aerodynamically-shaped vehicle with the beam reflected from a parabolic reflector onto a rectenna that operated with a high power density (figure 4-2). The rectenna was free to rotate and the DC power output was removed through slip rings.

A similar rotating arrangement is possible with the thin-film printed-circuit rectenna, but, because of its lower power density level, it would be necessary to rotate a much larger diameter. This led to the concept shown in Figure 4-3. Because of the very low mass of the rectenna this becomes a practical arrangement with a bicycle wheel-type of construction. The outer rim would be made of a lightweight, relatively stiff, graphite or boron fibre composite or it could be an inflatable torus. The wires to the hubs could be high-strength material and of very low mass. The rectenna would hang from the rim under a minimum of tension because it need not be normal to the arriving microwave beam to operate at high efficiency. The "bicycle wheel" has an elongated axle which has the dual function of supporting the rectenna wheel from the bearings in the top and bottom of the aerostat and bringing the DC power down to the area where the propulsion is likely to be installed.

The rectenna of the form just described is severely restricted in the conventional cigar-shaped aerostat. Such a shape has an exceedingly large displacement for a rectenna that is of optimum size from a microwave system point of view.

To obtain some inputs on aerodynamic shapes that would lend themselves better to the microwave power transmission system than the conventional streamlined dirigible-shaped vehicle, Dr. Norman Ham of the Aeronautical and Astronautical Department of The Massachusetts Institute of Technology was engaged to make a limited initial study. The results of this study are given in Appendix A.

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<sup>9</sup>Further study is required on the ground system design.

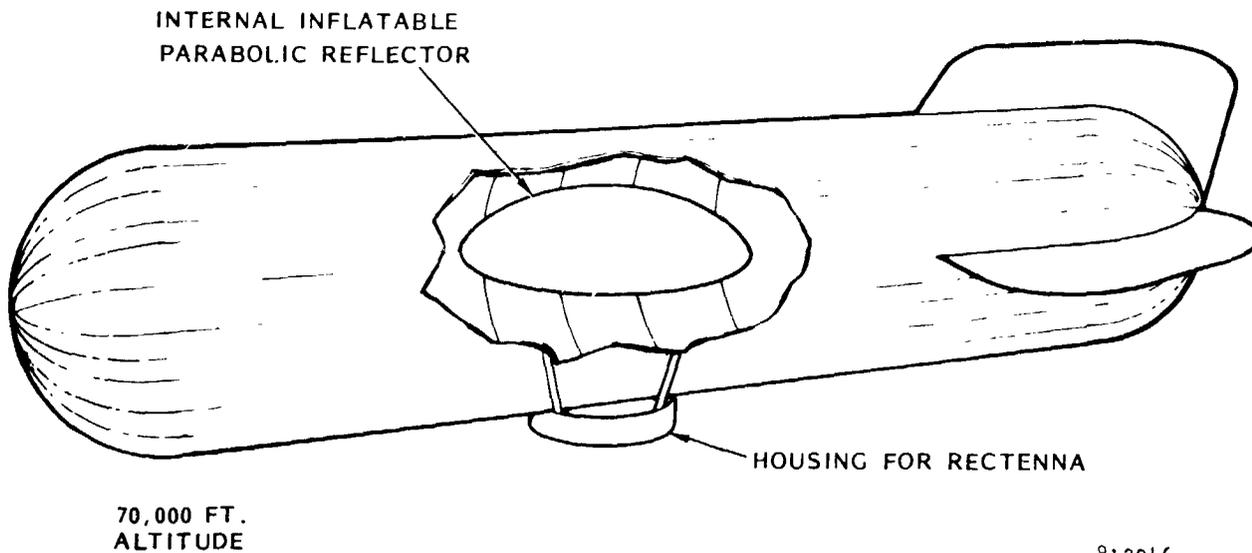


Figure 4-1. Artists Sketch Showing a Proposed Arrangement for Parabolic Reflector and Rectenna. The parabolic reflector concentrates the low power density microwave power to the density level at which the rectenna operates most efficiently. The resulting rectenna structure is sufficiently small and light in weight that it can be supported from the center and rotated, if necessary, to maintain alignment with the direction of linear polarization of the ground transmitting antenna.

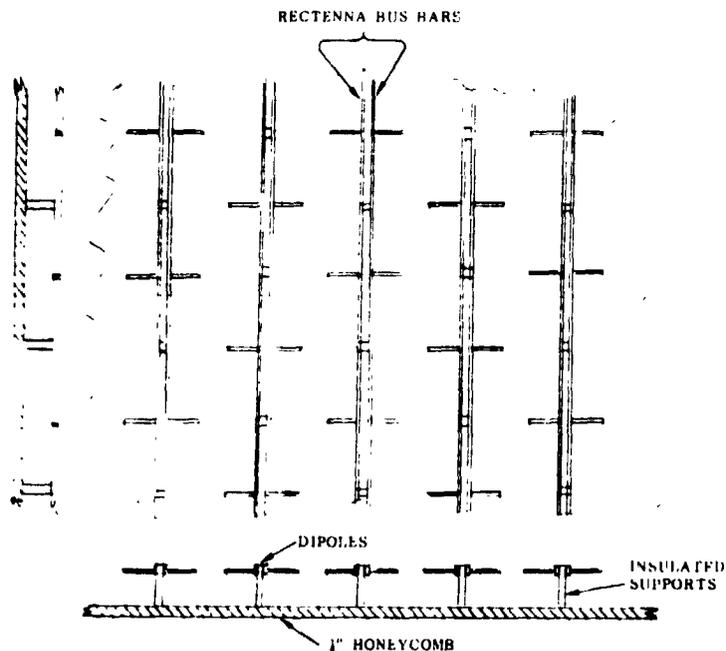
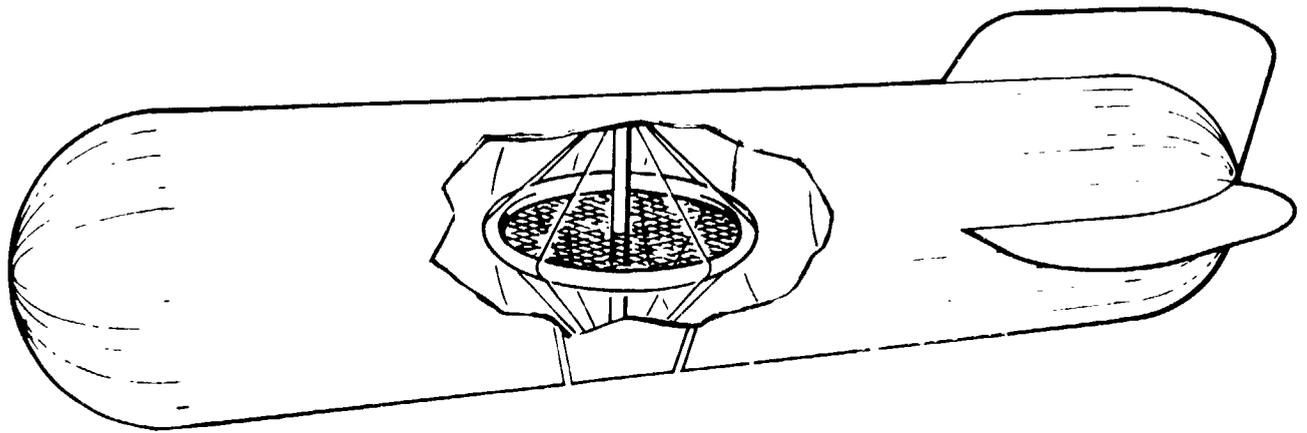


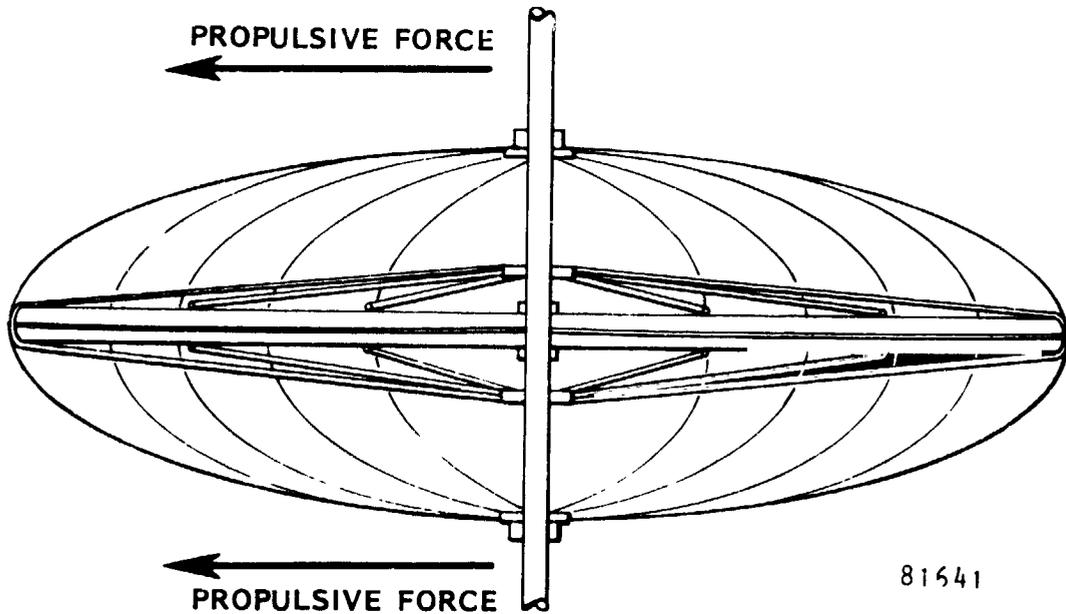
Figure 4-2. The Mechanical Construction of the Rectenna as Originally Proposed Utilized Lightweight Honeycomb as the Reflecting Plane. The buss bar of the rectenna foreplane had substantial mechanical strength and was combined with the honeycomb to form a structural beam with significant stiffness and mechanical strength.



70,000 FT.  
ALTITUDE

81640

Figure 4-3. Artists Sketch Showing the Proposed Arrangement for the Rectenna which is Supported on a Lightweight Bicycle-Wheel-type of Construction that is Free to Rotate within the Aerostat to Maintain Alignment with the Transmitting Antenna. Rim of wheel could be an inflated torus or a carbon or boron fiber reinforced construction.



81641

Figure 4-4. Symmetrically-Shaped Vehicle Cut in Half to Expose Internal Construction. Vehicle is given shape and rigidity by bicycle-wheel-type construction by launching and low altitude operation. Areas above and below bicycle spokes can be used for plenum chambers.

Dr. Ham was able to find some experimental data that had been taken on oblate spheroids that indicated a similar drag, a similar displacement, and a similar surface area to the conventional dirigible shape, but which could contain a rectenna of four times the area.

The circumferential symmetry of the oblate spheroid is especially attractive from the microwave system point of view because, with the proper propulsion, neither the rectenna nor the vehicle would have to rotate. Professor Ham briefly discusses one approach to the propulsion in his report.

It is probable that the application of propulsion to the oblate spheroid would require some rigid construction within this vehicle. An intriguing approach that combines the bicycle-wheel-type of construction to support the rectenna with a support for the propulsion as well, is the approach shown in Figure 4-4. Here the propulsion is mounted at the top and bottom of the oblate spheroid, free to rotate about the vertical axis so that thrust can be applied in any direction. By applying a differential thrust, the pitch of the vehicle can be changed to take advantage of any aerodynamic lift that the vehicle may have. A further possibility of the design shown in Figure 4-4 is the mounting of plenum chambers above and below the spokes to aid in the launching of the vehicle in its full aerodynamic shape at the surface of the earth.

To still take advantage of aerodynamic lift during periods of low wind speed, the vehicle would fly in circles but would not need to rotate with respect to the ground transmitting antenna. If a rotational torque is needed to maintain rectenna alignment with the transmitting antenna, a very small motor and propellor mounted on the periphery of the aerostat would suffice.

Another approach is to allow the vehicle to remain stationary but to use the aerodynamic lift of the vehicle and the large amount of microwave power to change the altitude of the vehicle as the wind velocity changes.

It is clear that such an approach to the vehicle problem as outlined above would introduce many new factors into the study but might well be the solution to the problem of maintaining control over the vehicle and supplying it with power from launch to station-keeping altitude. The present approach in which a bag of helium metamorphoses into an aerodynamically-shaped vehicle has a set of problems of its own, and the addition of a rectenna and propulsion to the structure makes this approach even more difficult.

In concluding this section, it is noted that one of the principle problems with any vehicle of the type just described is maintaining proper attitude (roll, pitch, yaw) and position. Fortunately, the microwave beam itself becomes an important element in the solution of the control problem as discussed in the next section.

## 5.0 ENGINEERING APPROACH TO THE POSITION AND ATTITUDE CONTROL OF THE AEROSTAT: THE RETRODIRECTIVE ARRAY PRINCIPLE AND NEEDS IN THE AEROSTAT

One of the general engineering problems with a microwave-powered atmospheric vehicle is the maintenance of proper attitude (roll, pitch, and yaw) and position (translation in x and y directions). To design a control system which will do this requires roll, pitch, yaw, and x and y translational references. Fortunately, a microwave beam provides all five of these references without any mass penalty to the aerostat and without need for calibration or reference updating at any time during the use of the system. Such a system for vehicle control purposes has been experimentally verified in one of the most difficult vehicles to control, the helicopter. A description of this control system and experimental verification is given in reference 14. Figure 5-1 shows the helicopter in stable flight.

Of course, sensors on the vehicles are required to sense the roll, pitch, yaw and translation of the vehicle with respect to the microwave beam reference, but these sensors are very simple and of almost negligible mass. The combined weight of the autopilot and the sensors on the helicopter weighed only 1.63 kg.

The same microwave beam that supplies the microwave power can be used for roll, pitch, and yaw sensing, but, if it is used for position reference, then the principle of the retrodirective array that is needed to focus the ground array on the atmospheric vehicle is lost. What is needed to make both principles effective and to allow for substantial maneuvering of the vehicle (for example, flying it in circles) is an auxiliary microwave beam positioned on the ground whose pointing direction is controlled from the ground and which therefore controls the position of the vehicle in the atmosphere. The retrodirective principle then makes use of a pilot beam mounted on the aerostat which controls the phasing and pointing of the microwave beam that supplies the power.

The sensors for roll, pitch, and yaw are independent of the shape of the microwave beam because they use the phase front and the polarization of the beam as references. The translational sensors, however, are sensitive to the shape of the beam, and become more sensitive as the beam becomes more narrow. It may, therefore, be desirable to use a much higher frequency for the auxiliary beam to minimize the aperture area of its ground-based transmitting antenna. This was the principle followed in the reference beam for the helicopter. An X-band (3cm) control beam was used, whereas the power beam would have been at a wavelength of 12cm. On the other hand, the use of a very high frequency beam for position control is probably prevented by the heavy absorption and even distortion of the beam by heavy rainfall. It is evident that tradeoff studies would be necessary to determine the best frequency for the position control beam.

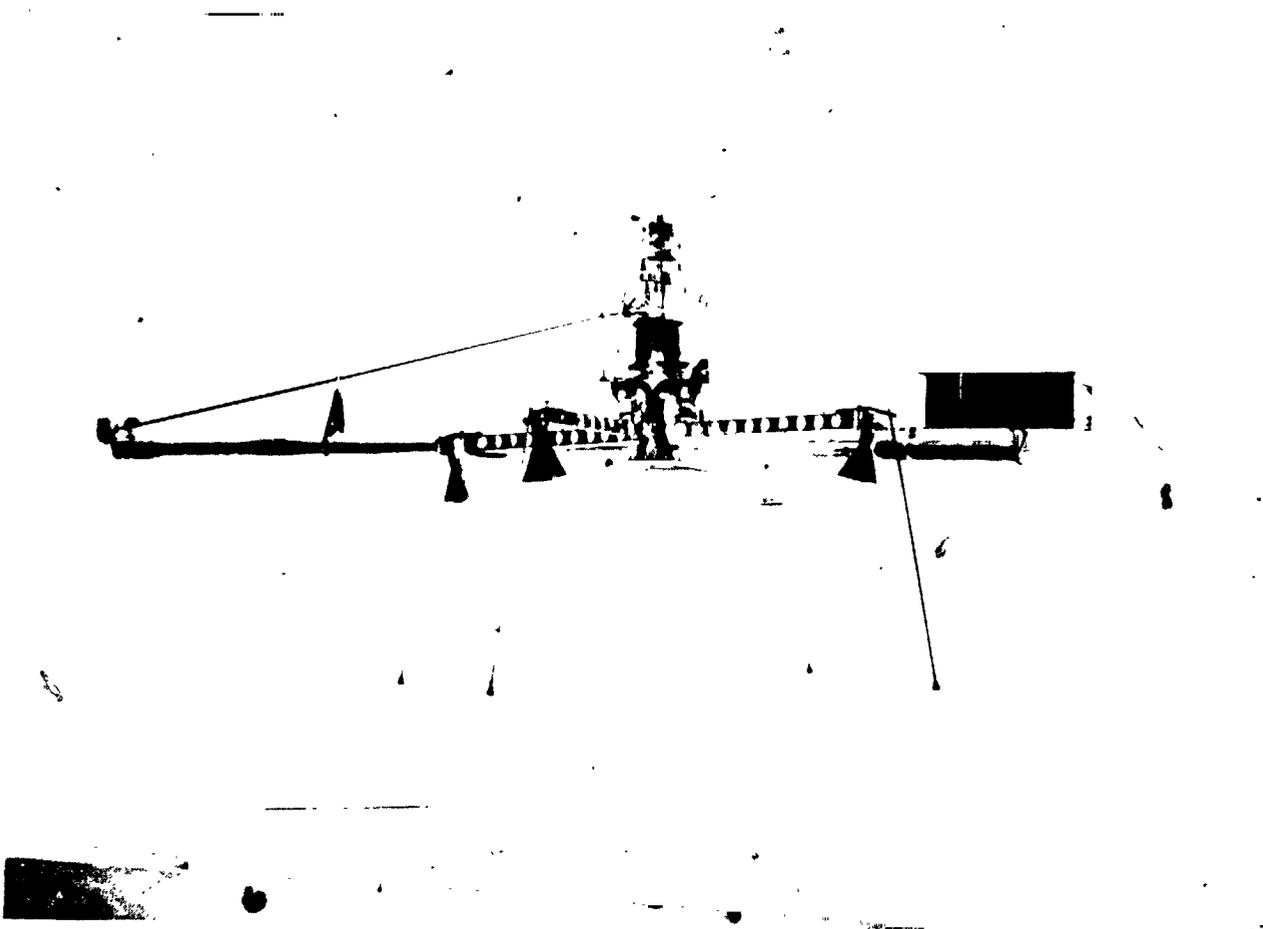


Figure 5-1. Position and Attitude Stabilized Helicopter Making Use of a Microwave Beam as a Position Reference in Free Flight Above a Landing Deck. Autopilot is carried on board the vehicle. Attached cables are for power and monitoring.

The retrodirective array principle is used to both properly focus and to direct the beam from the ground transmitting antenna directly at the rectenna in the microwave powered vehicle. Most of all, the electronics needed to implement this principle is designed into the ground transmitting antenna and is, therefore, not a part of this study. However, it is necessary to install a microwave pilot beam at the center of the receiving rectenna which is pointed in the general direction of the ground transmitting antenna and which supplies it with the phase information that is necessary to activate the retrodirective electronics in the ground array. The frequency of the microwave pilot beam is a microwave frequency that is near, but not at, the frequency used for the transmitted power beam from the ground array. The pilot beam needs to have an aperture small enough so that any normal roll and pitch of the air vehicle will not appreciably reduce the power density of the pilot beam when it reaches the ground array. Typically, this aperture would be about 0.5 meter in diameter. The power level of the pilot beam as it is emitted from the 0.5 meter aperture is subject to cost tradeoffs between the gain that is needed in each of the subarrays in the ground antenna and the mass and power penalty imposed upon the pilot beam to reduce the amount of gain that is needed in the ground array. The outcome of such a study is not known a priori, but it is probable that less than a kilowatt of pilot beam power would be needed, and that the total mass penalty for the pilot beam antenna and microwave power source would be no more than five kilograms.

## 6.0 EVOLUTION OF A PLAN FOR THE DEMONSTRATION OF A SCALED-DOWN VERSION OF THE MICROWAVE POWER TRANSMISSION SYSTEM IN COMBINATION WITH AN AEROSTAT VEHICLE

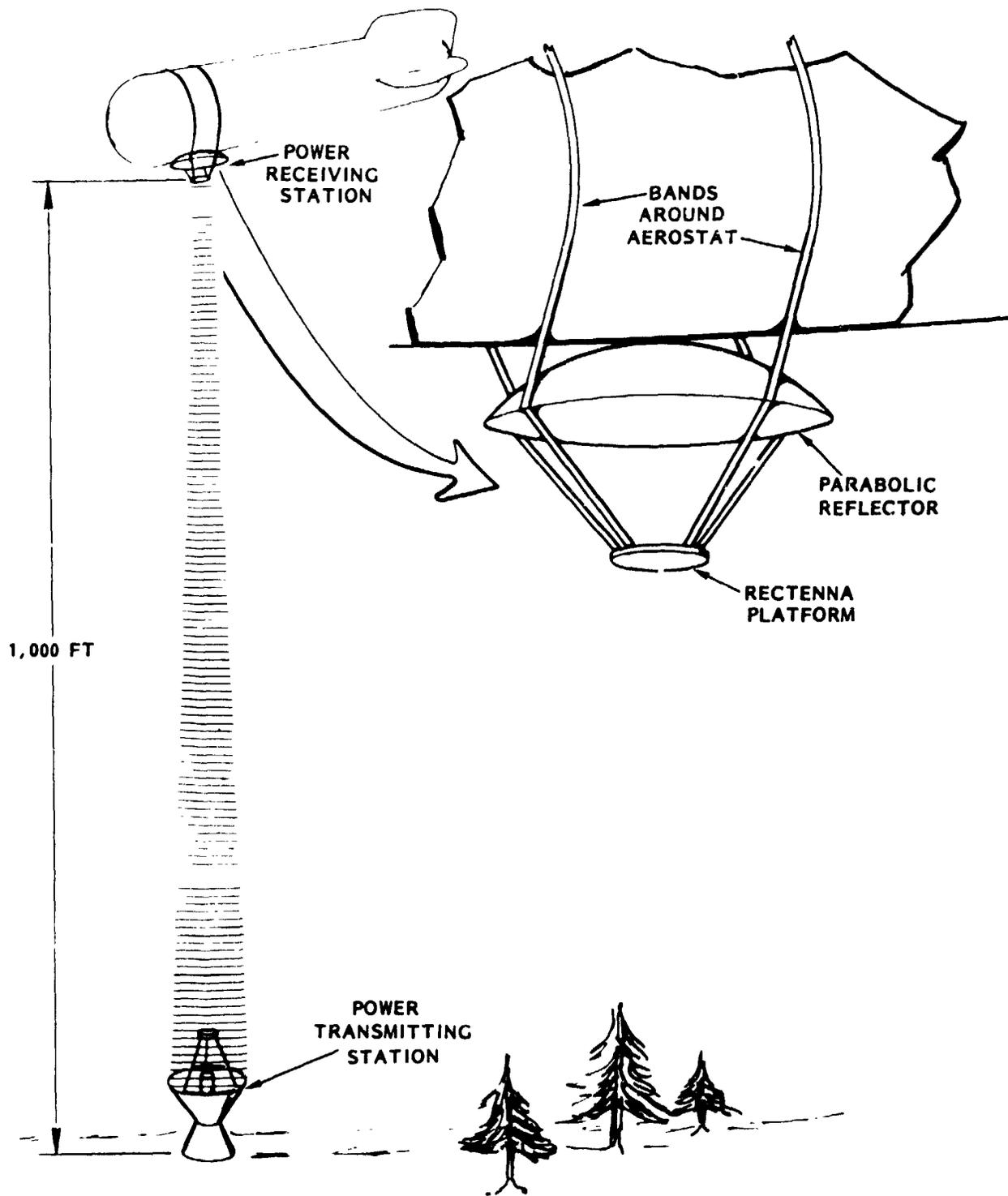
The generation of a plan to test a scaled-down version of the microwave power receiving system in an aerostat vehicle flying at low altitude was a part of the study. The purpose of the demonstration was to illustrate the approach to be taken to the full-scale system, using flight-weight hardware for the rectenna itself, but scaling down the system size to one of reasonable cost and requiring only a few months for construction and test. The demonstration as a minimum was to retain the lightweight rectenna construction.

As the overall study progressed, the plan for a demonstration went through three phases: (1) the plan originally conceived, submitted in the proposal, and partially firmed-up during the study (2) the plan as modified by the development of the thin-film printed circuit which was not a part of the original study, and (3) a new plan which involves not only the use of the thin-film printed circuit but also of a scaled-down version of an aerostat vehicle of a new design which can best accommodate the microwave power transmission system and which may have superior performance capabilities over the conventional vehicle. It is recognized that this last plan is a departure from the plan to utilize a conventional blimp and would not be a low-cost experiment, but the plan is consistent with the findings of the study that the conventional blimp or dirigible-shape is not the best shaped vehicle for the microwave power transmission system and that future plans for the study and the development of the microwave-powered high-altitude platform will have to take this into consideration.

### 6.1 The Original Plan for a Demonstration

The original plan may be best presented with the use of Figure 6-1. This plan to use a parabolic reflector that concentrated the collected microwave energy upon a rectenna much smaller in area was consistent with the original plan to use established rectenna hardware in the high altitude aerostat by combining it with a parabolic reflector which could be easily constructed to meet the relaxed tolerances made possible with the use of the rectenna in place of the usual horn-collecting device. This system had the advantage that the rectenna was sufficiently small to be able to rotate it easily to meet any change of heading of the vehicle.

The plan proposed the use of one of the 15.24 meter mechanically steerable parabolic reflectors at the Wallops Flight Center as the transmitting antenna. Since the antenna was used strictly as a passive receiver, it would be necessary to modify it and equip it with a microwave power source. An investigation of the best way to proceed with a low cost retrofit led to the conclusion that the use of a commercially-available six-kilowatt magnetron would be by far the lowest in cost. The original proposal was for a 3 kW tube, but the experiment is upgraded considerably without much additional cost by using the 6 kW tube.



812047

Figure 6-1. Proposed Demonstration of Flight-Weight Power Collection and Rectification System for Aerostat Use. Demonstration was configured to make use of available equipment and low cost components. About 600 watts of DC power could be obtained from flight-weight rectenna.

To allow an adequate reserve for contingencies in the overall execution of the proposed experiment, the balance of the design was carried out on the assumption of 3 kilowatts of generated power. Therefore, the details of the proposed plan, involving the altitude of the aerostat, the size of the collecting parabola and the power-handling capability of the rectenna were all set or controlled by the three kilowatt level of the generated microwave power.

It is assumed that 2.5 kilowatts of the original 3.0 kilowatts gets to the exciting horn on the transmitting antenna. Based upon an antenna efficiency of 60 percent, 1500 watts of the 2.5 kilowatts will get into the main beam.

On the receiving end of the system, the collection area of the parabolic reflector is to be determined. It is noted that the ratio of this collection area to the rectenna area should be approximately what was intended in the full-scale design of Figure 4-1, or a factor of about ten. Let us assume the same ratio in the demonstration unit. We further assume a collection efficiency of 50 percent of the main beam by the parabolic surface, with 80 percent of that appearing as DC power output from the rectenna. The 1500 watts at the transmitter has now decreased to 600 watts of power out of the rectenna.

To determine the rectenna area required, an average power output of four watts from each rectenna element will be assumed. Each rectenna element is associated with a cell area of 50 square cm so a total rectenna area of 7500 cm<sup>2</sup> is required, or an area about one meter in diameter. With the concentration ratio of ten to one, this defines the diameter of the collecting area as 3.18 meters.

Now if this diameter of 3.18 meters and an assumed diameter of 15 meters for the transmitting antenna is inserted into an approximate expression below for the relationship between separation distance, D, wavelength,  $\lambda$ , the transmitting aperture radius,  $r_t$ , and the receiving aperture radius,  $r_r$ , when the approximate efficiency is 50 percent as previously assumed, we find that the distance of transmission, D, is 306 meters.

$$D = \frac{\pi r_t r_r}{\lambda} \text{ for 50 percent transmission efficiency}$$

The vehicle can be flown at higher altitudes, of course, with the amount of energy captured by the parabolic reflector falling off as the square of the distance, approximately. A few tens of watts of power would be available at 1.85 kilometers.

A study was made of the feasibility of refocusing the transmitting antenna on a target 300 meters away. The semi-rigorous calculations that were made indicated that a movement of from .216 to .27 meters of the feed horn would be needed to refocus the energy on a collecting area 3.2 meters in diameter and 304.8 meters away. In the antenna that was being considered for the demonstration, there was ample room to mount a feed horn in the position needed to refocus the beam.

Automatic alignment of the transmitting beam on the receiving rectenna was assumed to be necessary. This was to be easily achieved by a set of sensors on the edge of the parabolic reflector on the balloon which would indicate if the beam were centered on the parabolic reflector. If it were not, then an error signal would be automatically generated and telemetered to the power system and gearing arrangement that controlled the pointing of the ground transmitter.

There was no cost estimate made of this particular experiment because of the desirability of converting the design of it to test the thin-film printed-circuit rectenna.

## 6.2 The Modified Plan for a Demonstration

The original plan to use a parabolic reflector and established rectenna hardware was abandoned with the development of the thin-film printed-circuit rectenna. However, from the overall demonstration point of view, the only modification was the substitution of the thin-film printed-circuit rectenna in the form of a deployable mat that would rap around the underbelly of the balloon.

The size of the proposed thin-film, printed-circuit rectenna was to have been  $9.29\text{m}^2$  to be consistent with the other features of the original plan. The construction of such a rectenna, fabricated in a sandwich construction with the thin-film printed-circuit on one face, the reflecting plane on the other face, and a lightweight foam as the material in between, was discussed with the Sheldahl Corporation. Sheldahl also suggested sealing the two film surfaces together at the edges of the rectenna to prevent the accumulation of moisture within the foam, and a reinforcing strip and the placing of eyelets to lace the rectenna to the balloon.

Also needed in the construction of the rectenna were 2000 diodes of a special design. While it is expected that such diodes will become low cost when built in reasonably large numbers, they are currently quite expensive.

The cost of these diodes, the additional development costs expected for the refinement of the thin-film printed-circuit design, the budgetary cost estimates from Sheldahl for the fabrication of the rectenna, and the integration costs (largely engineering), all added up to a figure that was out of the range of the anticipated budget for such an experiment.

A first estimate of the cost of this experiment based in part upon budgetary estimates obtained from Sheldahl for the fabrication of the rectenna and from the operation in Raytheon that fabricates the diodes follows:

Finish of development effort on rectenna	\$ 15,000
Procurement of 9.29m <sup>2</sup> rectenna from Sheldahl	\$ 29,800
Procurement of 2000 diodes	\$ 36,000
Art work for the printed circuits	\$ 5,000
	<hr/>
Subtotal for rectenna	\$ 75,800
Estimated cost of magnetron, its power supply, and associated interfacing with transmitting antenna	\$ 20,000
Engineering supervision	\$ 25,000
	<hr/>
Total	\$130,800

### 6.3 The New Approach to a Demonstration

The new plan for a demonstration retains the low-altitude, scaled-down features of the previous plans but goes much further in the overall concept of a high-altitude microwave-powered platform. It really consists of a series of tests and demonstrations designed to end up with a vehicle whose design has been largely determined by the microwave requirements and whose aerodynamic performance characteristics, propulsion, altitude and station keeping have been analyzed and verified by wind tunnel tests on scale models.

In this context, it is mandatory to work out a control system for the vehicle so that, with a set of attitude and position sensors and a set of propulsive units, it can automatically retain its proper position and attitude in the typical wind environment to which it may be exposed at high altitude. And the model should demonstrate this on a scaled basis at low altitudes. The control problem is expected to be fairly complex but a precedent has already been set for an experimentally successful system for the difficult hovering model of a free-flying helicopter that makes use of a weightless microwave beam as a position reference and only 1.36 kilograms of on-board sensors and autopilot as reviewed in Section 5.0.

What should such a vehicle look like? If the cue is taken from the requirements of the microwave power transmission system it would be circumferentially symmetrical and would not have to change its rotational orientation with a change in wind direction. It would not be a sphere but would have a thickness that would give it an appreciable lift because of its displacement volume while retaining an acceptable drag. To optimize the aerodynamic lift, it might be desirable to have the top half of a different contour than the bottom half.

In the context of searching for a new kind of vehicle, it should be recognized that the motivational drive should be to find a configuration that works best with the microwave power transmission system and not the reverse. The reason for this is that such an approach represents a completely new departure point where the probability of finding a new and optimum approach may be better than extrapolating from existing vehicle patterns.

In the event that a promising new approach is found, then the demonstration of a small-scaled vehicle becomes most important. Without the weight penalty and the safety precautions associated with the need for a human pilot, such a vehicle could probably be very economically constructed and demonstrated on a small scale. It would have the practical advantage of being able to fly directly off the transmitting antenna which would double as a launching and landing pad. The fact that it could utilize a slow vertical takeoff because of its neutral buoyancy makes it possible to use tethers in the early testing phase. In case of an emergency or malfunction of control, all propulsion could be shut off and the vehicle could slowly descend to the ground and be recovered without a crash landing.

It would also be possible to separate the vehicle and its control aspects from the microwave power aspect as, indeed, was the case in the microwave-powered helicopter in which the microwave-powered feature and the microwave beam-riding feature were separate phases.

## 7.0 SUMMARY OF THIN-FILM PRINTED-CIRCUIT RECTENNA CHARACTERISTICS OF GENERAL INTEREST

The purpose of this section is to summarize the expected characteristics of the thin-film printed-circuit rectenna for the vehicle and systems designer. Most of these characteristics have been obtained either experimentally, analytically, or both, as described in Section 3.0

### 1. DC Power Output - 130 to 200 watts/meter<sup>2</sup>

130 watts/meter<sup>2</sup> appears to be consistent with limited experimental data, computed dissipation capability of rectenna into ambient temperature of 30°C, and life as a function of diode temperature. 200 watts/meter<sup>2</sup> may be possible with additional development activity. Convection cooling could increase power-handling capability further.

### 2. Efficiency - 70 to 80 percent

Overall rectenna efficiency is the product of collection and rectification efficiency. Collection efficiency at the impedance match between space and the rectenna is close to 100 percent for the chosen DC load value. Rectification efficiency, which is the measure of conversion of collected microwave power to DC power, is currently 70 percent and, is expected to reach at least 75 percent with additional development, and could increase to 80 percent.

About the matched DC load point in terms of value of load resistance and load power, the efficiency changes very little with moderate departures from these values. An approximate expression for the collection efficiency, assuming the incident power remains unchanged and the breakdown voltage is not exceeded, is:

$$\text{Collection efficiency} = \frac{4R_L R_{LM}}{(R_L + R_{LM})^2}$$

where  $R_L$  is the load resistance and  $R_{LM}$  is the load resistance that gives a match to the incoming power.

A change in the load,  $R_L$ , by a factor of two from  $R_{LM}$  decreases the collection efficiency to 88.8 percent.

### 3. Mass of the Current Rectenna Design

Total measured mass of foreplane per square meter  
consisting of:

77 grams

1 mil Mylar	37 grams
copper conductors	30 grams
diodes	10 grams

- |   |           |
|---|-----------|
| Expected additional mass of reflecting plane and separators between the planes. | 50 grams  |
| Total expected mass per square meter  | 127 grams |
4. DC Power to Mass Ratio - kW/kg<sup>10</sup>

At 130 watts of DC power per square meter	1.02 kW/kg
At 200 watts per square meter	1.54 kW/kg
  5. DC Bussing Conductor Loss

Given by equations 3-16 and 3-22, a few percent for typical aerostat application. Negligible for high voltage, low power, or small area.
  6. Criticality of Orientation of Rectenna to Microwave Beam

Departures of up to 10° of the plane of the rectenna position perpendicular to the beam will not noticeably impact the rectenna efficiency.
  7. Criticality of Rotational Alignment of Rectenna with Transmitting Antenna

Efficiency will vary as the square of the cosine of the angular misalignment.
  8. Choice of Voltage and Current Output

Almost any voltage and current combination can be achieved by a series-parallel combining of the individual rectenna elements.
  9. Rectenna Failure Modes and Protective Steps

The diodes are the aspect of the rectenna that need protection. A short-circuit fault does not destroy the diode, but an open-circuit fault will. The protective device that is used not only for open-circuit faults but for any load condition that causes the rectenna output voltage to rise beyond a critical value is an electronic crowbar that short circuits the output of the rectenna for the duration of the unfavorable load condition.

The severest operational condition to protect the rectenna against is an inductive DC load and a sudden pulse of incident microwave power. This will fire the crowbar protective circuit for the rectenna and disable the system. With an inductive load, microwave power must be applied as a ramp function with buildup appropriate to the time constant of the inductive load.

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<sup>10</sup>Mass for rectenna only, no DC buss, auxiliary beams interface, etc.

10. Life

If run at a low-duty cycle (infrequent requirement to operate at rated power output), if protected from solar radiation that would tend to destroy the film, and if properly protected against load faults, the rectenna should have unlimited life. If continuously run at rated power output, the life would depend upon the operating temperature with rated power output, and life with the diode temperature.

11. Cost

A production cost of \$215/square meter has been estimated (See Section 2.3.3).

12. Environmental Considerations

If the system is designed for low specific cost (total microwave system cost divided by DC power output) and the rectenna is operated with an incident energy of 185 watts per square meter, the power density in the beam will be approximately the same at the transmitter as at the rectenna and will exceed the continuous exposure standard of 100 watts per square meter (or 10 milliwatts per cm<sup>2</sup> as it is usually specified). This should not be of concern to any object flying through the beam, where it would seem that the short term exposure standard of 1000 watts per square meter should apply.

Of more concern will probably be the radio frequency interference aspects of the harmonics generated by the rectenna. However, without a considerable amount of experimental data, from a fairly large rectenna, the seriousness of this problem cannot be properly evaluated.

The above items are considerations of the impact that the rectenna and the microwave beam may have upon the environment. The major impact of the environment upon the rectenna will be from the ambient temperature if the rectenna is housed inside of the airship which will protect it from wind and moisture.

13. Constraints for Operation of the Microwave Power Reception & Conversion System

The purpose of this item is to list all the constraints for operation of the Microwave Power Reception and Conversion system in one place.

- o The dipoles of the rectenna should be kept aligned with the direction of electric polarization of the transmitting antenna

- o The rectenna should be kept perpendicular to the axis of the microwave beam to within  $\pm 10^\circ$ , although further departure to  $20^\circ$  will not seriously impact the efficiency.
- o The output voltage of the rectenna should not exceed a preset figure. For a nominal 230-volt output, the preset figure might be 260 volts.
- o The rectenna should not be subjected to a step function of microwave power, particularly if the DC load tends to be inductive.
- o The rectenna tends to deliver constant power output regardless of load so that the voltage will climb rapidly as the power demand is reduced. In this context, power demand switching in large increments should not occur without the presence of an instantaneous load leveler device. This device could be a simple resistive load with a fast-acting transistor or similar device in series with it and a simple feedback loop to perform the desired function. The long-term treatment of load change would be to change the level of the transmitted power at the transmitter by telemeter link.
- o The diodes in the rectenna should not be operated at a temperature to exceed a predetermined figure set by life considerations.
- o The surface of the rectenna should be protected from the accumulation of water droplets between the circuit elements as this will seriously impact the efficiency.
- o The Mylar film or other organic material used in the rectenna should be protected from the sun's rays.

## 8.0 SUMMARY OF RESULTS

### 8.1 Rectenna for the Reference Design

The rectenna for the reference design had these constraints imposed by the work statement:

- o Frequency - 2.45 GHz
- o Incident power density upon rectenna - 175 watts/meter<sup>2</sup>
- o DC power output for propulsion - 43 kilowatts at 230 volts
- o DC power output for payload - 1 kilowatt at 28 volts
- o To be housed in or on a streamlined vehicle of 14,160m<sup>3</sup> (500,000 ft.<sup>3</sup>) displacement with a fineness ratio of 4 to 1
- o To be exposed to ambient pressure and temperature characteristics of 21,336 meters altitude.

In addition to these constraints there were the obvious ones of good efficiency, low mass, long life, ability to remain at a suitably low operating temperature for the solid state rectifiers.

Although it was not possible to complete the design with respect to the final assembly of the rectenna or determine just how the rectenna would be deployed on or in the vehicle, a detailed design of the foreplane was completed, favorable test results were obtained on a small section of the rectenna, and a detailed investigation of its heat-radiating ability was made. As a result of this work, a reasonably accurate specification of the characteristics of the reference design can be made. These specifications follow:

- o Area - 334 square meters
- o Mass - 43 kilograms (self-supporting when laced to or hung from a peripheral structure)
- o Efficiency (intercepted microwave power to DC power) - 75 percent<sup>11</sup>
- o Mass of DC collecting buss to hold I<sup>2</sup>r loss to 1 percent of power collected - 1.2. kilograms
- o DC power output - 43 kilowatts at 230 volts  
- 1 kilowatt at 28 volts
- o Protective circuitry; crowbars used to short DC power output of rectenna, in case of open-circuit or high impedance load. Additional mass represented by protective circuitry is two kilograms.

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<sup>11</sup>Anticipated

o Life - 10,000 hours at full duty cycle when operated in a 30°C environment.

### 8.2 Development of a Production Cost Model for the Entire Microwave Power Transmission System

The development of this cost model is based upon rigorous laws of diffraction that control the transfer efficiency of microwave power from the transmitting to the receiving aperture, and upon the estimated cost of components which have recently become much better defined. The model mathematically minimizes the cost when values for aperture transfer efficiency, wavelength, distance from transmitter to receiver, cost of rectenna and transmitter construction per unit area, and cost of microwave power per unit of power, are inserted into the cost model relationship. Thus the cost model applies over a very wide range of parameters.

When the model is applied to the set of constraints of altitude, wavelength, and incident microwave power density, that appear in the work statement, the production cost varies between \$560,000 for the reference rectenna design of 44 kilowatts of DC power output and \$1,267,000 for 300 kilowatts of DC power output. The ground power requirement for a minimum-cost 44-kilowatt design is actually greater than for the minimum-cost 300-kilowatt design.

### 8.3 First Phase Development of a Thin-Film, Printed-Circuit Rectenna

This development, initially unplanned, arose from early study investigations that indicated the desirability of such an approach. Because there was no prior rectenna art that used this approach, it was necessary to establish the validity of the approach by designing, constructing, and testing a small sample of such a rectenna. The rectenna development also involved repackaging of the special GaAs Schottky-barrier diode chip that is required for this application in a form suitable for mounting on the rectenna. The repackaging is also consistent with a planned approach to cutting the cost of the diode, now the principle element of cost in the rectenna.

This development has established the efficiency, DC power output density, and mass per unit of power output, of a rectenna suitable for aerostat use at 21,366 meters. In addition it has provided a much better base for accurately estimating the projected rectenna costs because printed circuit production is a well-established business.

### 8.4 Initial Investigations of Vehicle Designs that are More Consistent with the Needs of the Microwave Power Transmission System

The microwave power transmission system requires that the rectenna remain aligned with the transmitting antenna. As the wind changes direction, this means that either the vehicle's shape must be insensitive to the direction of the wind, or that the rectenna must rotate with respect to the vehicle to retain its alignment. Also to accommodate a rectenna large enough in diameter to optimize

the microwave power transmission system from the viewpoint of specific cost (cost per unit DC output), the conventional dirigible shape has a displacement volume associated with it that is very much larger than anything so far considered.

Recognizing this problem, an initial effort to look at other aerodynamic shapes from the viewpoint of drag, mass, etc., was made. The investigation discovered a set of data on a prolate spheroid which, if valid, could point the vehicle study and development activity away from the conventional shapes.

8.5 The Estimated Cost for the Completion of the Development of the Thin-Film Printed-Circuit Rectenna and the Construction of a Full-Scale Rectenna Meeting the Requirements of the Reference Design

The development and associated costs were broken down into a series of activities as given below. The uncertainty cost range for each of the activities is also given. The costs are assumed to be in 1980 dollars.

	<u>Estimated Cost</u>	<u>Range</u>
o Finish up initial development effort on foreplane	\$ 10,000	\$ 7,000 - 13,000
o Finish up development of combined foreplane and reflecting plane and separator	7,000	5,000 - 10,000
o Fabricate one square meter and test in the pressure and temperature environmental typical of 21,336m altitude	40,000	30,000 - 60,000
Total Development Costs:	<u>\$ 57,000</u>	<u>\$ 42,000 - 83,000</u>
o Design and fabricate full scale rectenna for reference design:		
Effort other than diode fabrication	\$117,000	\$ 90,000 - 150,000
Diode fabrication	350,000	140,000 - 700,000
Total:	<u>\$467,000</u>	<u>\$230,000 - 850,000</u>

It is obvious from the above cost breakdown that the one which is least under control is the cost of the diodes for the full-scale rectenna. The development item which is the least under control is the combining of the foreplane with the reflecting plane and separators.

## 9.0 CONCLUDING REMARKS AND RECOMMENDATIONS

This study has developed a substantial technology and cost base, for a low-mass, reasonably efficient, long-life rectenna, that will operate on or in an aerostat vehicle at 21,336m. This is consistent with the original objectives of the study. However, the most important finding of the study may be the incompatibility between the needs of the microwave power transmission system with respect to minimizing specific cost (cost per kilowatt) and the conventional dirigible-shaped vehicle. The reference design calls for a rectenna of  $9.9^{12}$  meters radius which will produce 44 kilowatts of DC power output in an aerostat with a displacement volume of  $14,160\text{m}^3$ . A 26-meter radius rectenna will produce 300 kilowatts of DC power but the system cost increases by a factor of only 2.5. The power drain from the electric utility system is actually less for the 300-kilowatt system than it is for the 44-kilowatt system, reflecting the impact that the dimensions of the rectenna have upon the power transfer efficiency.

A dirigible-shaped vehicle that will internally support a circular rectenna of 26-meter radius is a tremendously large vehicle. Further, the need for the rectenna to rotate within the vehicle would complicate the vehicle and rectenna design.

Although the microwave power transmission system for the  $14,160\text{m}^3$  aerostat is not optimum from the specific cost point of view, it may still be acceptable if there were not other factors involved.

Microwave system and cost, however, may be a secondary issue. The primary issue may very well be how to launch and get such a vehicle to 21,336m where the microwave power feature may take over. It is in this particular area where the availability of microwave power in much larger amounts than in the reference design may make it possible to design a hybrid type of vehicle whose lift is partly supplied by natural buoyancy and partly supplied by aerodynamic lift resulting from propulsion force or from tilt rotors that could be used for both lift and for overcoming wind drag. It is possible that such an approach may make it possible to design a vehicle that can utilize the flat-bed microwave transmitting antenna as a launching pad and then ascend nearly vertically under microwave power to mission altitude. The general problem, of course, is with the considerable wind that may be generally expected at altitudes where the air density is still appreciable. Such a condition places a premium on a vehicle that has a combination of low drag and large amounts of power for propulsion.

It is, therefore, recommended that a vehicle study be made that supports the kind of approach just outlined. It is also recommended that this study give adequate attention to control systems that will assure the attitude and position stability of the vehicle, and that a plan be outlined which will include obtaining experimental information with respect to controlled launching of a scaled test vehicle and demonstration of complete control and station-keeping capability at a low altitude.

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<sup>12</sup>Based on  $P_d = 185 \text{ w/m}^2$

The rectenna study has done much to define the receiving portion of the system and it has provided an estimate of overall microwave power transmission system costs. However, the technical details of the ground portion of the microwave power transmission system have not as yet been defined. Because there have been very significant contributions within the past two years with respect to new transmitter technology and ability to cost the ground portion of the system, it is recommended that the scope of the rectenna study be expanded to include the design and detailed costing of the transmitter. Such a study should include all of the details of the retrodirective array approach to the design of the transmitter.

There is also the need to continue with some aspect of technology development that will contribute to the eventual design and construction of the entire microwave power transmission system. A considerable amount of development still remains to be done on the thin-film printed-circuit rectenna before even a square meter of it can be constructed. And when a square meter of it is constructed for testing, the testing should include testing at the ambient pressure and temperature conditions typical of the 21,336m aerostat application. This development effort could be completed with modest financial support. A larger effort would be that associated with building a relatively small area of the ground-transmitting antenna and testing it out as a retrodirective array.

At some time these intermediate steps will have to be taken before an attempt is made to design a full-scale microwave power transmission system in complete detail. Indeed, the intermediate steps are necessary to uncover problem areas and to provide confidence in the successful outcome of the larger effort.

In conclusion, it may be stated that this study has done much to increase confidence in being able to design and construct a satisfactory microwave power transmission system for an aerostat vehicle and in estimating its cost. It has also established a better perspective on the overall system which includes the aerospace vehicle as well as the microwave power transmission system. The results are compatible with the hoped-for technical feasibility of the overall system but indicate that new approaches to the vehicle design may be desirable and should be examined.

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APPENDIX A

Investigation of the Oblate Spheroid as a Possible  
Configuration for a High-Altitude Powered Platform

INVESTIGATION OF THE OBLATE SPHEROID AS A POSSIBLE CONFIGURATION  
FOR A HIGH-ALTITUDE POWERED PLATFORM

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July 27, 1979

SUMMARY

The oblate spheroid is compared with the conventional airship shape in terms of aerodynamic drag, lifting volume, hull surface area, and rectenna reflective or capture area required for station-keeping at an altitude of 70,000 feet. A spheroid with a height-to-diameter ratio of 0.4 is found to be a feasible alternative shape for a high-altitude powered platform. Some discussion of control requirements is included.

DISCUSSION

Baseline Airship

For comparative purposes a baseline conventional airship having the following characteristics was chosen from Ref. 1:

Length	$l$	250 ft.
Diameter	$d$	63 ft.
Volume	$V$	500,000 ft. <sup>3</sup>
Drag Coefficient	$C_{D_v}$	.06

At 70,000 feet, the atmospheric properties of interest are:

Density	$1.39 \times 10^{-4}$ slugs/ft. <sup>3</sup>
Kinematic Viscosity	$21.3 \times 10^{-4}$ ft. <sup>2</sup> /sec.

Then at 50 knots wind speed the Reynolds number is

$$\begin{aligned}RN &= 50 \times 1.7\ell / 21.3 \times 10^{-4} \\ &= 40,000\ell\end{aligned}$$

where  $\ell$  = hull length.

Then for the baseline airship,  $\ell = 250$  ft., and  $RN = 10^7$ .

From Ref. 2, P. 6-19, the empirical drag coefficient based on  $V^{2/3}$  for smooth wind-tunnel models is given by

$$C_{D_V} / C_f = 4(\ell/d)^{1/3} + 6(d/\ell)^{1.2} + 24(d/\ell)^{2.7} \quad (1)$$

where  $C_f$  = skin friction coefficient

Then for the baseline airship,  $\ell/d = 4.0$  and

$$C_{D_V} / C_f = 8.07$$

Therefore, the baseline value of  $C_{D_V} = .06$  implies that

$$C_f = .06 / 8.07 = .00745$$

But at a Reynolds number of  $10^7$ , Ref. 2, P. 3-12, suggests a value  $C_f = .004$  for use with Equation (1). It is evident that the baseline drag coefficient has been approximately doubled, presumably to account for roughness, interference, tail surfaces, etc. For consistency, a factor of 2.0 will be applied to spheroid wind tunnel data to account for the same effects.

### Spheroid Geometry

For comparative purposes, three oblate spheroids of height-to-diameter ratio  $h/d = 0.20, 0.30, \text{ and } 0.40$  were chosen. The volume of an oblate spheroid, from Ref. 3, P. 2-43, is given by

$$V = \frac{\pi}{6} d^2 h$$

Then to maintain the baseline volume of 500,000 ft.<sup>3</sup>, the following dimensions are required:

h/d	h, ft.	d, ft.
0.20	33.8	169
0.30	44.1	147
0.40	53.6	134

#### Aerodynamic Drag

Figure 1, from Ref. 4, presents wind-tunnel drag data for oblate spheroids of various h/d in terms of drag coefficient based on planform area  $\pi d^2/4$ . The corresponding values for  $C_{D_V}$  are presented below for the case  $C_{L_i} = 0$  and  $M \leq 0.25$ :

h/d	$C_{D_V}$ (RN = $3.3 \times 10^6$ )	$C_{D_V}$ (RN = $16 \times 10^6$ )
0.2	.018	.018
0.3	.0216	.035
0.4	.0223	.050

The corresponding values of Reynolds number and  $C_{D_V}$  (by linear interpolation) for the three spheroids under consideration are:

h/d	l = d	RN	$C_{D_V}$	$2C_{D_V}$
0.2	169	$6.76 \times 10^6$	.018	.036
0.3	147	$5.88 \times 10^6$	.024	.048
0.4	134	$5.36 \times 10^6$	.027	.054

The doubled value includes roughness, interference etc., as discussed previously. It is seen that the spheroids have drag coefficients that compare favorably with the baseline airship value  $C_{D_V} = .06$ .

### Surface Area

From Ref. 3, P. 2-43, the surface area of an oblate spheroid is given by

$$S = \frac{\pi d^2}{4} \left[ 2 + \frac{1}{e} \left( \frac{h}{d} \right)^2 \text{LN} \frac{1+e}{1-e} \right] \text{ ft.}^2$$

where  $e = [1 - (h/d)^2]^{1/2}$

For the three spheroids under consideration:

h/d	S, ft. <sup>2</sup>
0.2	48,800
0.3	40,000
0.4	35,900

Ref. 2, P. 6-18 gives the surface area of a typical airship:

$$\begin{aligned} S &\approx 0.75 \pi l d \\ &= 37,200 \text{ ft.}^2 \text{ for the baseline airship} \end{aligned}$$

It is seen that the spheroid of  $h/d = 0.4$  has less surface area, and therefore requires less hull fabric, than the baseline airship.

### Rectenna Reflective and Capture Area

The reflective surface required by the rectenna is ideally a paraboloid having a cross-section given by

$$y^2 = 4 f x \quad (2)$$

where  $f$  = focal length

Equation (2) is plotted in Figure 2 for the case where  $f = 0.833$ . Also shown is an oblate spheroid cross-section of  $h/d = 0.4$ . Note that the

spheroid cross-section closely approximates that of the paraboloid over two-thirds of the radius (or diameter) of the spheroid. The corresponding rectenna capture area is seen to be  $\pi(0.67d)^2/4 = 6320 \text{ ft.}^2$  for  $d = 134 \text{ ft.}$  With the slight modification to the spheroid contour shown in Figure 2, the rectenna capture area is increased to  $\pi(0.8d)^2/4 = 9,030 \text{ ft.}^2$ . The associated rectenna areas (at hull bottom) are  $564 \text{ ft.}^2$  and  $999 \text{ ft.}^2$  resp.

Alternatively, if a thin film rectenna is used, no reflective surface is required, and the rectenna capture area becomes  $\pi d^2/4 = 14,100 \text{ ft.}^2$

#### Control Considerations

An advantage of the oblate spheroid shape is its independence of wind direction, which means that an airship having this shape can maintain a fixed heading with respect to the surface of the earth, thus simplifying the station-keeping control problem. Also, it is no longer necessary to cross-polarize or mechanically rotate the rectenna due to heading changes.

A cursory examination of the workshop proceedings referred to in Ref. 1 gives the impression that the problems of stability and control of high altitude powered platforms are under-emphasized in the literature. For the present case under consideration of an airship having an oblate spheroid shape, it is believed that three propellers of approximately twenty-five feet in diameter might be required, spaced equidistantly around the circumference of the spheroid, such that the thrust axis of any one propeller is at 120 degrees to those of the others. Through reverse pitch it is then possible to provide the equivalent full thrust of two propellers in any horizontal (wind) direction. In addition, it will be necessary for each propeller to swivel moderately in both the vertical and horizontal sense to provide proper control of airship pitch, roll and propeller torque, i.e., heading.

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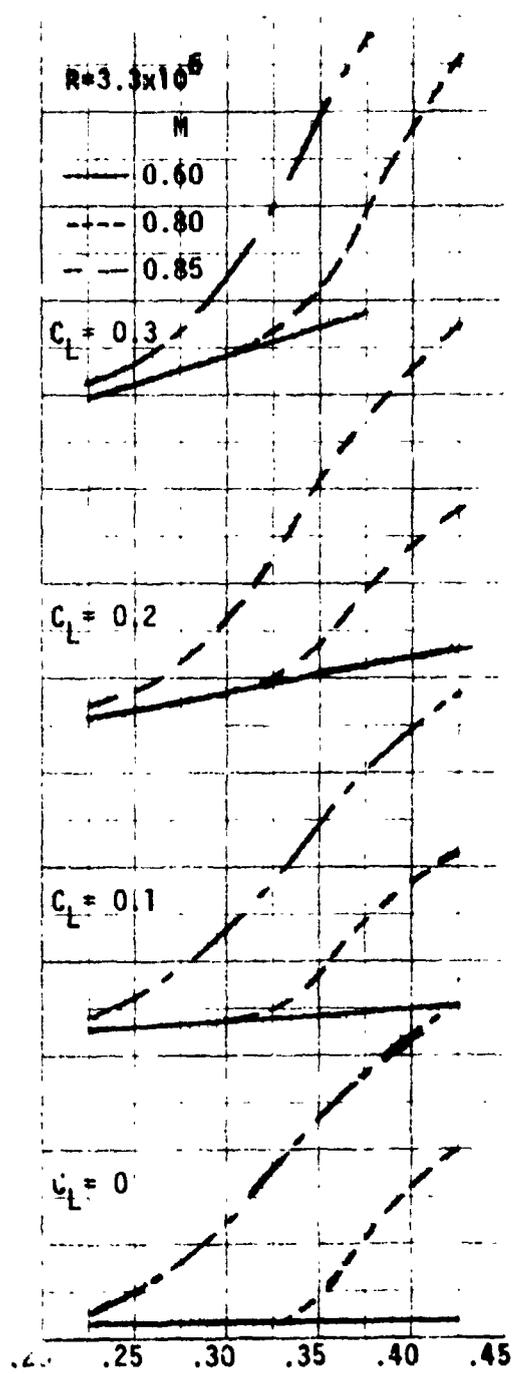
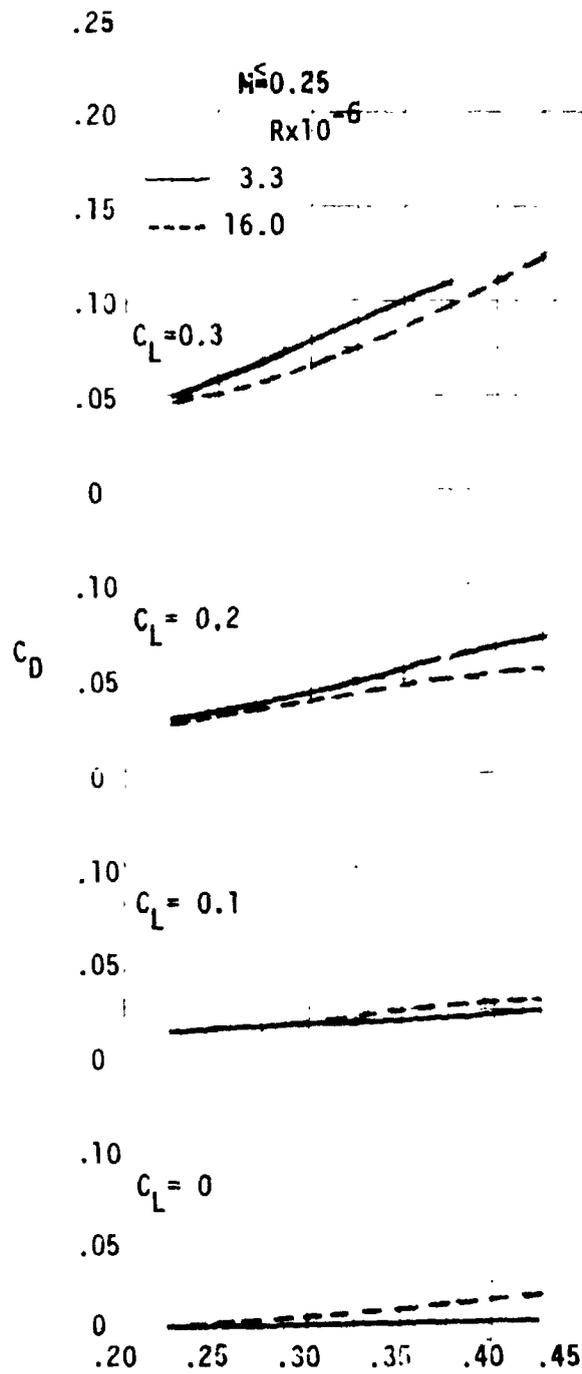


Figure 1. - The variation with height - diameter ratio of drag coefficient at constant lift coefficient.

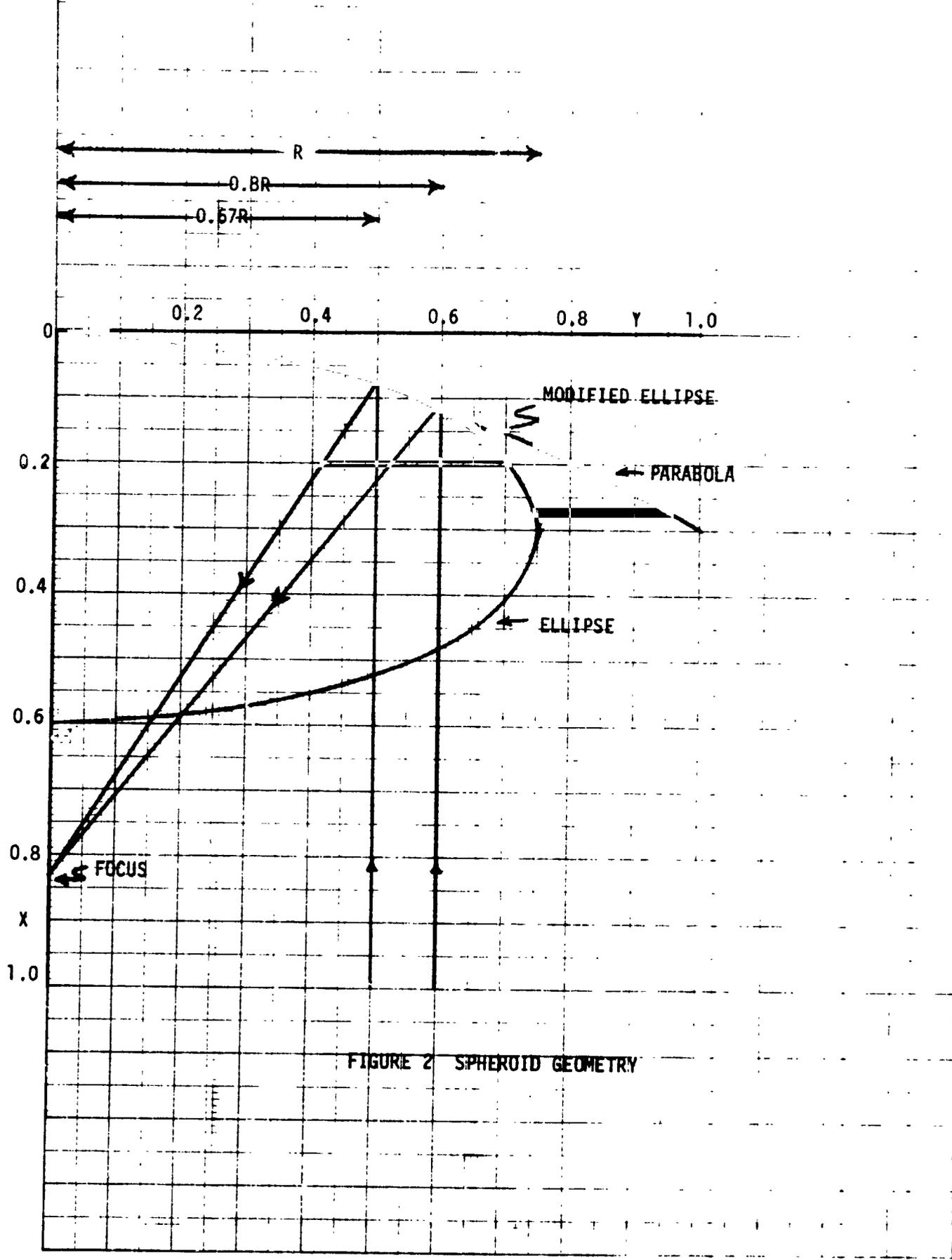


FIGURE 2 SPHEROID GEOMETRY